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CAUSES OF CATASTROPHE

Earthquakes, Volcanoes, Tidal Waves, and Hurricanes

by L. Don Leet

—At exactly 2:45 p.m., September 21, 1938, a hurricane swept up Long Island, destroying everything in its path. Buildings toppled, city streets were submerged, communication and transportation were paralyzed and four hundred and ninety-four people were killed. It was New England's worst disaster.

What were the forces behind this sudden calamity? Why did it start? Just what are the underlying causes of catastrophes that strike the world? Will science someday be able to predict accurately when these sudden changes in nature will occur?

L. Don Leet, professor of seismology at Harvard University, answers these questions clearly and simply in his fascinating account of nature's manifestations. Causes of Catastrophe presents up-to-date scientific thought on the causes of earthquakes, volcanoes, hurricanes, typhoons, and tidal waves, and in the process explodes some of mythology's theories—the giant in the mountain, the girdle of serpents—which still

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TIDAL WAVES, AND HURRICANES

by

L. Don Leet

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Whittlesey House
McGRAW-HILL BOOK COMPANY, INC.
NEW YORK : LONDON

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The quality of the materials used in the manufacture of this book is governed by continued postwar shortages.

PUBLISHED BY WHITTLESEY HOUSE
A Division of the McGraw-Hill Book Company, Inc.

PRINTED IN THE UNITED STATES OF AMERICA

Preface

Violent manifestations of nature have frightened man or excited his inquisitiveness since time immemorial. Yet it is only within the past few decades that we have begun to struggle toward a true understanding of many of the features of such phenomena as earthquakes, volcanoes, tidal waves, and hurricanes.

The purpose of this book is to review our knowledge of these forms of catastrophe, with a view to answering some of the questions that are frequently asked by individuals with a healthy curiosity but no special training in these phases of geophysics.

I am particularly indebted to Edward A. Schmitz, the principal illustrator, for his unique understanding and handling of the pictorial problems. The drawing of the trough of low pressure that guided the 1938 hurricane into New England was made by Harold F. Lindergreen, as were the three illustrating the principles of the seismograph's operation and of certain types of wave motion. The last three were made available through the courtesy of The Hercules Powder Company.

Contents

Culmination of Catastrophe

TOKYO AND YOKOHAMA

During the early hours of Saturday, Sept. 1, 1923, squalls and cloudbursts of a dying storm lashed the Japanese shores in the vicinity of Tokyo and Yokohama. By ten o'clock in the morning the skies had cleared and these cities lay sweltering under an early fall sun with no premonition that their hour of doom was about to strike.

As noon approached, preparations for the midday meal went forward in thousands of homes; across the yard next to a Catholic church on the central portion of the bluff overlooking Yokohama, a sacristan hurried toward the tower to ring the Angelus bell. As he reached the portal, the ground suddenly lifted under his feet, the high altar began to dance, a gaping crack opened in the vaulting overhead, and the two towers and the vault of the church crashed to the ground. It was the work of seconds. The sacristan turned in dazed awe to see, stretching away from the foot of the bluff, a picture of complete devastation where a few moments before had been a flourishing city of a half-million population with all its homes, places of business, and handful of modern buildings.

The earthborne waves of destruction swept onward. Twelve miles beyond Yokohama, at the Tokyo suburb called Ōmori (Great Forest), Henry W. Kinney, editor of the *Trans-Pacific* magazine, was on a Yokohama-bound train. In his words:

> As if it had slid suddenly into a sea of tossing, choppy waves, the coach pitched up and down, lurched drunkenly from side to side. The passengers clung to the seats.

"Why the devil doesn't the fool stop the train?" growled the Englishman opposite me.

But we were already slowing down.

"*Jishin* (earthquake)," yelled a Japanese, pointing out of the window.

I glanced out just as the stone face of an embankment shot down over the tracks. It did not slide or tumble down: it literally shot down, as if compelled by a sudden, gigantic pressure from the top, the stones spreading in a twinkling over the wide right-of-way. A four-story concrete building vanished, disintegrated in the flash of an eye. Tiles cascaded with precipitate speed from the roofs. The one predominating idea that struck the mind was the almost incredible rapidity of the destruction.

The conductor came to the front of the car, doffed his cap, scorning to let even an earthquake interfere with courtesy. "I'm sorry. This train will not proceed further toward Yokohama."

The earth waves swept on to Tokyo. At the Imperial University, Professor Akitsune Imamura was sitting in his office at the Seismological Institute. There:

At first, the movement was rather slow and feeble, so I did not take it to be the forerunner of so big a shock. As usual, I began to estimate the duration of the preliminary tremors, and determined, if possible, to ascertain the direction of the principal movements. Soon the vibration became large, and after 3 or 4 seconds from the commencement, I felt the shock to be very strong indeed. Seven or 8 seconds passed and the building was shaking to an extraordinary extent, but I considered these movements not yet to be the principal portion. At the twelfth second from the start, according to my calculation, came a very big vibration, which I took at once to be the beginning of the principal portion. Now the motion, instead of becoming less and less as usual, went on increasing in intensity very quickly, and after 4 or 5 seconds I felt it to have reached its strongest. During this epoch the tiles were showering down from the roof making a loud noise, and I wondered whether the building could stand or not. I was able accurately to ascertain the direc-

tions of the principal movements and found them to have been about NW or SE. During the following 10 seconds the motion, though still violent, became somewhat less severe, and its character gradually changed, the vibrations becoming slower but bigger. For the next few minutes we felt an undulatory movement like that which we experience on a boat in windy weather, and we were now and then threatened by severe aftershocks. After 5 minutes from the beginning, I stood up and went over to see the instruments. . . . Soon after the first shock, fire broke out at two places in the university, and within 1½ hours our Institute was enveloped in raging smoke and heat; the shingles, now exposed to the open air as the tiles had fallen down due to the shock, began to smoke and eventually took fire three times. I cannot tell you how desperately I fought against the fire without water or any help from outside, commanding at the same time the rest of the men to carry away the more important things into safe places. It was 10 o'clock at night before I found our Institute and Observatory quite safe . . . we all, 10 in number, did our best, partly in continuing earthquake observations and partly in extinguishing the fire, taking no food or drink till midnight, while four of us who were residing in the lower part of the town lost our houses and property by fire.

A curious psychological twist at such times is the conviction each person has that he is at the center of the worst disturbance. It didn't occur to people in Tokyo that Yokohama was badly affected, or the reverse. Mr. Kinney and his companions, struggling on foot toward Yokohama, met a stout, begrimed man who said, "You from Tokyo? I hear you people in Tokyo were lucky, not much of a quake, only fire." Yes, "only fire," which wiped out 71 per cent of one of the world's largest cities. Karuizawa, an inland mountain resort at the foot of volcanic Mt. Asama where foreigners were wont to escape the summer heat and humidity of the coast cities, was shaken but undamaged as the earth waves swept by. A story goes that there, B. W. Fleisher, owner of the *Japan Advertiser*, world-famous English-language paper in Tokyo, rushed a telegram to Tokyo to stop

the presses for a story on the Karuizawa quake. Those presses were stopped, but they never ran the story.

Soon after the quake, great dust clouds which hovered over Yokohama and Tokyo were ominously augmented. Over Yokohama "a huge cloud had appeared, rolling up swiftly into the clear blue—an uncanny thing, dense to the point where it seemed ponderous, dull brown and black, shot with sulphur, sinister, menacing." Uncontrolled fires were raging.

Within 30 minutes, fire had broken out in 136 different places in Tokyo. In all, 252 started and only 40 were extinguished. Authorities estimated that at least 44 were started by chemicals. A 12-mile-per-hour wind from the south spread the flames rapidly. This shifted to the west in the evening and increased to 25 miles per hour, then shifted to the north. These changes in direction added greatly to the area burned. Within 18 hours, 64 per cent of the houses in Tokyo had burned, and the fires died away after 56 hours, with 71 per cent of the houses consumed, a total of 366,262. The spread of fire in Yokohama, originally a city of a half million population, was more rapid. Within 12 hours 65 per cent of the city had burned. It was eventually gutted 100 per cent.

The city of Tokyo had grown as a series of concentric rings around the old imperial walled city which is now the location of the Imperial Palace in the ward of Kojimachi. To the east of this are the business districts of Nihonbashi (Bridge of Japan) and Kyobashi (Bridge of the City) which, in turn, are bounded on their east by the Sumida River separating them from the wards of Honjo and Fukagawa. The worst fires started in these low-lying and congested areas. The higher residential districts ringing Kojimachi to the north, west, and southwest escaped the greatest damage from fire.

Fire was also the great killer. One Yokohama incident, described by Kinney, was typical of thousands:

A man called to me, "Here, help me get my wife out." She was caught by the waist. Her entire upper body was free, and she was staring at us and straining, slim, jewelled hands pressing frantically at the great beam that held her, unhurt, but tightly pinned. Half of the beam was covered by bricks. We might as well have tried to lift a house. We tugged away, helplessly. We caught at men who rushed by, called to them to assist. One or two stopped, but most of them shook themselves free. I wanted to hit them. It seemed so damnably callous. And still, they also had wives, children, somewhere in their homes on the bluff, and were obsessed by the anxiety to find them, to know. I wanted to get home too, but I couldn't leave that woman. And then the flames came and drove us back. I had to half strangle that poor devil to pull him away. The roar of the flames drowned her cries. So I rushed along.

A spectacular event in Tokyo is described in the words of Professor S. Nakamura:

The most unhappy and sad catastrophe of this sort happened on a tremendous scale at the now notorious ground formerly occupied by the Clothing Department of the Army in Honjo. This is a piece of quite open ground . . . and near by, separated only by a street, there is an extensive garden of a wealthy banker, Mr. Yasuda. . . . Thus we had an area of . . . about 250 acres, lying just on the eastern bank of the River Sumida. People assembled here from all quarters to save their lives and property. What a sad fate it was for those seeking refuge, not knowing in the least the impending calamity! According to eyewitnesses, the whole space was so thickly packed with men, women, and children and their belongings that they found themselves almost unable to move.

At four o'clock on Sept. 1 fire approached from three sides, leaving only the side next to the river. Suffocating fumes and horrible fires threatened the unhappy people, sparks falling over them in showers. All at once the people heard some unearthly sound approaching them, the heavens darkened, and they were terror-stricken to find that a furious tornado was sweeping toward them,

lifting or setting in flames everything before it. When it had passed over the ground, what was left behind? The charred remains of 35,000 human beings!

Later, the exact number of victims was reported to have been 38,015. About 2,000 others, for the most part those seated in the southern corner of the ground, survived. One report stated that the majority were terribly burned, but there were many who showed no effects of heat on skin or clothing and their death was apparently due to suffocation.

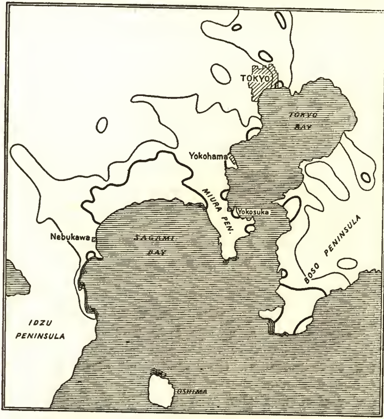
Tokyo, Yokohama, and Yokosuka, the great naval base, are on the shores of Tokyo Bay, which opens southward into Sagami Bay. The source from which the earthquake waves radiated was under Sagami Bay. Along its shores destruction was widespread. People were still trying to dig their way out of collapsed buildings near the water when a new menace bore down upon them—a tidal wave.

Shortly after the quake, the waters of Sagami Bay receded from the Oshima, Atami, Miura, and Boso shores as though from an unprecedentedly low tide, exposing miles of sea bottom. Then it returned rapidly, inexorably, to a height of 30 feet. It perched boats crazily on top of collapsed buildings, and dragged buildings back into Sagami as it returned to the bay.

The combined forces of earthquake, fire, tornado, and tidal wave had turned those Kwanto shores into a laboratory demonstration of catastrophe on a gigantic scale. Final figures on casualties and damage were conflicting. One authority listed for the entire area 99,333 killed, 43,476 missing, and 103,733 injured, with 128,266 houses completely collapsed, 126,233 half collapsed, 447,128 burned, 868 washed away by tidal waves, for a total of 576,262 houses completely destroyed by one means or another.

Within 4 hours, 132 aftershocks had been felt in Toyko; in 24 hours, 237. During September, the first month following the

quake, there were 718 aftershocks; in October, 96; in November, 86; in December, 139; in January, 167. The increases in De-



Map of region in Japan affected by earthquake of Sept. 1, 1923. Heavy lines enclose areas within which 30 per cent of buildings were destroyed by shaking; light lines, 5 per cent. Wavy lines along coast indicate regions swept by tidal waves.

cember and January preceded and followed a large shock on Tuesday, Jan. 15, 1924, the first earthquake I ever felt. What an impressive welcome to a strange land it was! Following that,

activity waned, and by November, 1925, Professor Imamura wrote: "And now the people of Tokyo, Yokohama, and other places in the vicinity are enjoying the usual tranquillity from seismic activity peculiar to their district, namely, two shocks a week on the average."

ST. PIERRE, MARTINIQUE

Volcanoes, too, have contributed to the world's catastrophes. A historic instance occurred on the island of Martinique in the West Indies a few minutes before eight o'clock on Thursday morning, May 8, 1902. Eyewitness stories in the news accounts of that event describe a spectacular scene. Mt. Pelée (Bald Mountain), which rises over 4,400 feet on the northern tip of the island, supplied the eruption. On its southern slope was the coastal city of St. Pierre with a normal population of 25,000 augmented to about 40,000 by refugees fleeing other parts of the island during the days preceding. It had a picturesque assemblage of early seventeenth-century architecture.

For days, the crater had been active with repeated minor explosions, throwing hot mud and rocks about, with heavy falls of ash on the surrounding country, and pillars of fire over the peak at night. One account states that the people were frightened, but the governor of the island, "wise in his own conceit," stationed soldiers around the city to preserve order and prevent panic-stricken flight. Then, within a matter of minutes on the morning of May 8, a great blast of flaming gases swept down the mountainside and wiped out the town, leaving only one survivor, a prisoner in the local jail. The fate of the residents was shared by the governor and his soldiers.

Assistant Purser Thompson of the *Roraima*, one of the ships lying off St. Pierre that morning, said:

I saw St. Pierre destroyed. It was blotted out by one great flash of fire. Nearly 40,000 people were all killed at once. Of 18 vessels

lying in the Roads, only one, the British steamship Roddam, escaped, and she, I hear, lost more than half on board. It was a dying crew that took her out. Our boat arrived at St. Pierre early Thursday morning. For hours before we entered the roadstead, we could see flames and smoke rising from Mt. Pelée. No one on board had any idea of danger. Captain G. T. Muggah was on the bridge, and

The cloud of flaming gases that swept down the slopes of Mt. Pelée, Island of Martinique, and destroyed the city of St. Pierre at about 7:45 A.M., Thursday, May 8, 1902. Forty thousand persons were killed.

all hands got on deck to see the show. The spectacle was magnificent. As we approached St. Pierre, we could distinguish the rolling and leaping of the red flames that belched from the mountain in huge volumes and gushed high in the sky. Enormous clouds of black smoke hung over the volcano. The flames were then spurting straight up in the air, now and then waving to one side or the other a moment, and again leaping suddenly higher up. There was a constant muffled roar. It was like the biggest oil refinery in the world burning up on the mountain top. There was a tremendous explosion about 7:45, soon after we got in. The mountain was

blown to pieces. There was no warning. The side of the volcano was ripped out, and there hurled straight toward us a solid wall of flame. It sounded like thousands of cannon. The wave of fire was on us and over us like a lightning flash. It was like a hurricane of fire, which rolled in mass straight down upon St. Pierre and the shipping. The town vanished before our eyes, and then the air grew stifling hot and we were in the thick of it. Wherever the mass of fire struck the sea, the water boiled and sent up vast clouds of steam. I saved my life by running to my stateroom and burying myself in the bedding. The blast of fire from the volcano lasted only a few minutes. It shriveled and set fire to everything it touched. Burning rum ran in streams down every street and out into the sea. Before the volcano burst, the landings of St. Pierre were crowded with people. After the explosion, not one living being was seen on land. Only 25 of those on the Roraima, out of 68, were left after the first flash. The fire wave swept off the ship's masts and smokestack as if they were cut with a knife.

Earthquakes

VERY MISCELLANEOUS IDEAS ON CAUSES—PREHISTORY TO 1755

The earth has, without any doubt, been shaken periodically from place to place by the vibrations which we call earthquakes since long before genus *Homo* began to walk around on his hind legs. On this dying cinder in space, myriads of biological parasites have been terrified and puzzled by the phenomena. When man joined this group, he, too, failed to understand natural events, but he was never at a loss for words to discuss them and their significance. Thus we have had preserved for us a record of human thoughts on the subject of earthquakes, along with volcanoes, hurricanes, and assorted catastrophes.

From the beginning, certain individuals showed an aptitude for sensing the personal advantages of appearing to possess inside information explaining natural events, especially the violent and the unusual. Lacking facts, these alert ones inevitably relied heavily upon imagination. The first ideas took the form of animal analogies and, with growing popular demand, drew more and more upon the supernatural.

Shaking the Earth's Support

One of man's early rationalizations about his surroundings attempted to explain the manner in which the earth was supported in its place among the stars. After it was realized that some support was necessary for it to maintain an independent

position while the stars, sun, and moon completed their cycles, it was easy to conclude that shaking of the earth was due to motion of the support. This suggested life, and experience with beasts of burden argued for animals as the form of life performing this duty. Belief that an animal of some kind supported the earth and, by moving, caused earthquakes was as widespread among aboriginal tribes as belief in some form of existence after death.

On the islands of Bali and Flores, among the Dyaks of Borneo, on the west coast of the Malay Peninsula, in Bulgaria, and among the Mussulmen of Constantinople, the buffalo, symbol of force, was the animal that bore the earth on its back and caused earthquakes when, tired by its immense burden, it shifted its weight from one foot to another.

Among the Algonquin Indians of North America, the tortoise was under the earth. In the Celebes, the motion was explained by the hog, which supports the earth while scratching himself on a palm tree. In the Moluccas, it was a serpent; in Persia, a crab; on Sumatra, the serpent Naga-Padoka. The lamas of Mongolia assured their devout followers that after God made the earth, he placed it on the back of an immense frog, and every time the frog shook his head or stretched one of his feet there was an earthquake immediately above the part that moved. This refined version of inspired doctrine was a major advance in seismological theory, for it had the merit of explaining the local character of earthquakes, with which Mongolians were more familiar than many benighted outlanders.

The Brahmans of India had a tradition which bridged the gap between the theory which pictured animals supporting the earth and that which assumed the earth floated on water. Vishnu, the number two person of the Hindu Trinity (Brahma, Vishnu, Siva), after having killed the serpent Hirani Ashshana, which had stolen the earth and concealed it in the seventh heaven, succeeded in finding the earth again and returning it

to the water where it belonged. But all was not yet well. He immediately perceived that instead of floating, as it had done when created by Brahma, it settled lower and lower and finally

Cause of earthquakes, according to the lamas of Mongolia: when the frog lifted a foot, there was an earthquake immediately above the part that moved.

began to sink. Quick as a flash he decreed that the seven serpents charged with the guardianship and illumination of the seven segments of the lowest heaven should take turns supporting the earth. Thereafter, each time one arrived to take over, the earth trembled as it was transferred to its new support.

The concept of an earth floating on water was attributed by Seneca to Thales, but it may well have originated in India. Thales held that the hypothesis of a floating earth was proved by the frequency with which craterlets of sand are formed by water gushing from the ground in major earthquakes. He compared the earth to a boat which rolls until it ships water. Seneca

opposed the theory on the simple but conclusive grounds that it required earthquakes caused by rocking of the earth-boat to be world wide, which they are not.

The learned discussions of this hypothesis were above the popular level of interest or understanding, but the picture of an earth floating on water was implicit in many legends describing fish which support the earth, such as the Hebrew marine monster, the leviathan. The Masawahilis, of East Africa, are credited with a poetic version of seismic folklore along these lines: In the universal ocean swims a fish called the Chewa. It carries on its back a stone upon which there is a cow which carries the earth on one of its horns. When the cow becomes weary and shifts the load to the other horn, there is an earthquake.

MYTHOLOGY'S CONTRIBUTION

In time, a feeling got around that perhaps this was asking too much of the known strength of everyday animals, so it became popular to invent fantastic beings liberally endowed with the necessary energy. At this stage, seismic theories left the realm of folklore and entered that of mythology.

The ancient Greeks, who placed the world on the shoulders of Atlas, neglected to accuse him of complicity in causing earthquakes. The Tlascaltans of old Mexico believed that the earth was flat and rested on the shoulders of certain divinities; it shook when, to rest themselves, they moved their burden from one shoulder to the other. Among southern Californian aborigines the duty was performed by seven giants. Certain tribes of Colombia, South America, believed that the earth was originally supported on three beams which terminated in a near-by forest. The god Chibchacum, however, once playfully flooded the plain of Bogotá and was punished by the god Bochica, who commanded him to carry the earth on his shoulders.

Sometimes the mythical being was reclining and jarred things by turning over onto the other side.

According to belief of the Senegambians, when God made the earth he placed it on the head of a giant. Trees, plants, and every growing thing were his hair and living things his parasites. When the earth was placed on his head, he was seated facing the east. Occasionally he turned around to face the west but did this so quietly that nobody noticed it. If he then turned to face the east again, however, he jarred houses down, overthrew trees, and raised general havoc. This explained why the strongest shocks always seemed to come from the west.

The Manicheans believed that the earth was carried on the shoulders of the giant Homophore; it trembled when he fought with the giant Splenditenens. Ancients of the Ougandi, in Africa, passed on the word that the earth rested on a rock in Lake Victoria, where a son of Musasa, god of the lake, lived; it shook when he walked around too fast.

According to the Wanyamwasis, the earth was a disk supported on one side by the mountain Lugulu, or Lugyia, and on the other by the giant Nyamu Titinwa. His wife, Fumyolo, supported the sky. The earth trembled when Nyamu petted Fumyolo—a touching thought. In Lettonia, the god Drebkhuls was credited with carrying the earth and causing it to shake when he moved. The Karens, of Birmanie, called him Shie-Ou and believed that he was placed under the earth by the sun-god Ta-Ywa.

On the island of Nias, near Sumatra, there developed a new trend in these philosophies which has persisted through many a modern counterpart. Ba-Ouvando, wicked spirit who supported the earth, made it tremble to punish inhabitants who failed to make proper sacrifices to him.

According to a reported Rumanian legend, the earth is supported by three pillars, Faith, Hope, and Charity. If one of

these virtues wanes on earth, the pillar corresponding to it shrinks, and the earth trembles out of balance until God stabilizes it again. It's anybody's guess which pillar got out of line in Rumania on Nov. 10, 1940.

In another case, the support is somewhat more material. At Capacci, near Palermo, Sicily, it was believed that the Jew Malco, for having struck Christ as he climbed Calvary, was condemned to turn unceasingly the column of iron that supports the earth as a sort of materialized axis. His penance was to last until Judgment Day. From time to time he became desperate and tried to end it all by striking the iron column in the hope that the earth would crumble.

In ancient Egypt, the earth was visualized as a plate completely surrounded by a mountain range. It rested on a great emerald, reflections from which caused the sky to appear blue. When God wished to cause an earthquake, he commanded the emerald to shake the earth's roots, and if it were not for the mountain range encircling and protecting it as a ring does a finger, the ground would be shaking continuously.

Some legends tell of the earth's having a girdle of serpents. In Burma, one aboriginal tribe believed that the earth trembled when one of these mistook his tail for prey and set out after it in the hope of catching up to a good meal.

Personification of the earth was popular in many places. Seneca related that many philosophers regarded the earth as a living being. Ovid told how, when the sun came too close as the result of a crooked course which Phoebus gave his chariot, the earth's surface was burned and it trembled in terror as it tried to protect itself with its hand. Aristotle turned that belief to account by comparing seismic movements to the shaking of a man in the grip of fever. To show how such things get around, that was the literal belief of the Kaffirs of Mozambique, who, at the time of a severe earthquake on Aug. 22, 1891, told a missionary that the earth had chills and fever. In lighter vein, there

was traced to Peru the belief that earthquakes occur when the earth dances.

A short step from the simple personification of the earth were mythological beliefs which assigned control of various phenomena to a galaxy of gods. Among these was Poseidon (Neptune to the Romans), whom the Greeks regarded as controlling all matters pertaining to the waters of the earth. Because of the number of submarine shocks, this came to include jurisdiction over all earthquakes as well. One of the more puckish pranks of Poseidon, as related by Xenophon and by Plutarch, was to cause a terrific earthquake which chased King Agis from his conjugal couch, never to return, and caused him to regard his son Agesilaus as a bastard.

THE ARISTOTELIAN SCHOOL

The Greek, Aristotle (384–322 B.C.), of Stagira, became a commanding figure on the scientific stage. In *Stagiritae Meteorologicorum* (liber IV, Edicion de Casaubon, Aureliae Allobrogum, MDCV; a Latin translation of the original Greek), he summarized and refuted some previous theories and then pronounced his own judgment on the causes of earthquakes so convincingly that his ideas were still being quoted as authority at Marblehead, Mass., in 1727.

He dealt in particular with theories of Anaxagoras of Clazomena, Democritus of Abdera, and Anaximenes of Miletus. Anaxagoras, it seems, held that the "ether" frequently agitated the earth in escaping from collapsing caverns and veins. This "ether" of Anaxagoras appears to have differed essentially from the ether of more modern physics, which penetrates all substances and fills outer space, as an intangible essence of the imagination called in to explain the propagation of light through space. Anaxagoras' "ether" was more nearly analogous to gases, in particular to the atmosphere. Anaxagoras stated that

his ether entered the upper parts of the earth dissolved in rain water; that Nature proclaimed that all parts of the earth be equally porous and slightly compacted and the element *earth* be divided into an inhabited upper part floating in a gaseous lower part. He demonstrated that the known inhabited part of the earth was curved, spherical, gibbous, and humped, but his ideas about the causes of earthquakes, as handed down through Aristotle, are not explained in enough detail to bring them out of an ethereal fog into the light of understanding. Democritus believed that the earth became surcharged with water and earthquakes resulted when excess water moved from one part to another. Anaximenes correlated earthquakes with excessive drought or rain, on the theory that the earth cracked and broke either when dried out or when swollen by excessive water. Living in the middle of the sixth century before Christ, Anaximenes thus expounded the first known theory connecting earthquakes with meteorological phenomena. The supposed connection between drought and earthquakes did not survive in popular belief, but the possible effect of rainfall in producing earthquakes is still discussed in current seismological literature.

Aristotle, after presenting objections to the theories of his predecessors, some reasonable and some not, proceeded to formulate his own, just as hypothetical though beautifully logical. They were not seriously or successfully challenged for a score of centuries. He launched a thousand ships of fantasy; he left nothing unexplained, for he was unhampered by facts. Upon a vague concept of the mechanism of evaporation accelerated by heat, with the four elements of antiquity's universe —*fire*, *air*, *water*, and *earth*—as building materials, he constructed a series of philosophical gems and scientific absurdities. He combined the phenomena of hurricanes, volcanoes, and earthquakes indiscriminately. His basic mechanism for producing earthquakes was the forceful escape of *air* imprisoned

by *earth*. He carefully explained how earthquakes could be more numerous at times of eclipse of the moon, though they aren't; how earthquakes could occur most frequently in the midst of a tempest, which they don't. One small thought was sufficient to beget any generalization. In spite of the rise of observational habits, we still have our Aristotles about us in science as well as in politics.

Aristotle's facile pen and nimble wit impressed all and sundry to such an extent that even today ghosts of his theories are walking. One of them is the popular impression in some countries that "earthquake weather," a sultry, oppressive day, augurs catastrophe. This was argued originally because *air* was supposed to have gone into *earth* in excessive amounts, leaving the atmosphere short, and would necessarily have to escape soon to restore normal balance, thus causing an earthquake. A Japanese seismologist, Omori, took cognizance of this widespread belief in his country and investigated conditions on the occasion of 18 catastrophic earthquakes there between 1361 and 1891. The weather was fair or clear for 12, cloudy for 2, rainy or snowy for 3, rainy and windy for 1, humid and sultry "earthquake weather" for 0.

Even our literature carries the Aristotelian imprint. In Shakespeare's *Henry IV*, where Glendower boasted that the earth was shaken at his birth, Hotspur replied:

> Diseased nature oftentimes breaks forth
> In strange eruptions; oft the teeming earth
> Is with a kind of colic pinch'd and vex'd
> By the imprisoning of unruly wind
> Within her womb; which, for enlargement striving,
> Shakes the old beldam earth, and topples down
> Steeples and moss-grown towers.

In the official government report on the Long Beach, Calif., sometimes known as the Los Angeles, earthquake of Mar. 10,

1933, Aristotle again intruded through a report of Professor Charles C. Conroy, cooperating with the Weather Bureau office at Los Angeles, beginning, "In view of the widespread popular belief that earthquakes are associated with a certain type of close, sultry weather, a detailed account of meteorological conditions at Los Angeles on March 10 and 11 will not be without interest." The account describes a somewhat hazy day, with maximum temperature of 70° and relative humidity slightly above normal, but not at all excessive. "In the late afternoon the air was filled with a peculiar bluish haze, resembling a veil of smoke. At 4:30 P.M., he (Professor Conroy) called the attention of Mark H. Stanley, of the Weather Bureau, to this phenomenon. At 4:45 P.M., a sheet of alto-stratus cloud moved up rapidly from the west and at 5:10 P.M. had entirely covered the sky. This cloud sheet persisted but thinned gradually after 6:45 P.M., and the moon shone through with increasing brightness in the evening." The earthquake occurred at 5:54 P.M. There was nothing abnormal about the conditions described, nor any reason for associating them with the earthquake. The recitation of such events is of interest chiefly because it is still necessary to mention them in connection with earthquakes.

In the Middle Ages, it was further proposed that the subterranean vapors were affected by stars, especially by Mars and Jupiter. As recently as 1935, an amateur prophet in New York City based startlingly inaccurate earthquake "predictions" on miscellaneous conjunctions of heavenly bodies, in the best manner of Conrad of Megenburg in 1359.

Following the lead of the inhabitants of Nias whose Ba-Ouvando punished those who failed to make proper sacrifices, Europeans gradually swung to the theory that supernatural control was dominant. It was even given a scientific tinge by van Helmont in 1682, when he stated that the mechanism involved an avenging angel who struck the air so as to give rise to

a musical tone from which vibrations were communicated to the earth. Stukeley, in the early eighteenth century, stated: "The chastening rod is directed to towns and cities, where there are inhabitants, the objects of its monition—not to bare cliffs and uninhabited beaches."

Theologians seized earthquake-given opportunities to urge upon their parishioners fear of the wrath of God. The Reverend John Cotton, pastor of the Church of Christ, delivered and published, "A Holy Fear of God and His Judgments, Exhorted to in a Sermon at Newton (Mass.), Nov. 3, 1727, On a Day of Fasting and Prayer, Occasioned by the Terrible Earthquake That Shook New England on the Lords-Day Night Before, With an Appendix Containing a Remarkable Account of the Extraordinary Impressions made on the Inhabitants of Haverhill. . . ."

In another sermon occasioned by the same earthquake and preached late in 1727 by the Reverend John Barnard of Marblehead, Mass., is found a collection of many of the ideas about the causes of earthquakes current at that time. Most of them will be recognized as tracing directly back to Aristotle:

. . . by earthquakes is not to be understood the general and constant motion of the earth, by which, as is supposed, it performed its daily round upon its own axis, or its yearly one in its assigned orbit; but I mean particular shocks given to some part or other of the earth by which the surface of it, here or there, is put into an unusual and violent motion which is carried forward on the surface of the earth in an undulating manner, like the rolling waves of the sea; and sometimes, it may be, by a more direct motion from the centre, by which the earth heaves up till it bursts, and swallows what is near it, in the gaping chasm. . . .

Causes of an earthquake . . . may be considered either as natural or supernatural . . . it is rational to suppose that there are caverns and hollownesses in the earth, containing wind or water or both. Lesser ones we find in our digging of wells . . . there are

subterraneous fires in the bowels of the earth . . . these fires approaching near caverns must give a vehement agitation to them . . . as the fire under a pot sets the water aboiling in it . . . the wind and water put into violent motion by the heat seek a vent or room to expand . . . therefore the surface of the earth is thrown into motion. . . .

Effects are numerous . . . sometimes houses reel to and fro . . . while vessels upon the waters feel the shock as tho they were running upon a gravelly bottom or rafts had suddenly rushed against them. . . . Channels of water, the rivers, have been diverted from their usual courses thereby. Sometimes a mighty roaring noise has accompanied an earthquake. Some have thought that an earthquake gives vent to venomous subterranean fumes which have produced pestilential diseases. When earthquakes happen, it is the Lord of Hosts that visiteth a place therewith. . . . God has been visiting us with this tremendous judgment this week. How terrible was the first sudden shock there of the last Lords-Day Night, a little before Eleven, when the most of us were in our beds, and were awakened with a most hideous roaring and terrified with the rocking of our houses, the rattling of our windows, and doors, and the earth shaking under us. . . . And how was the shock repeated ever since, both day and night, though in lesser rumblings? And this has happened, not to a particular town or place, but so far as we can learn to the whole land.

In 1755, the Reverend Thomas Prince, one of the pastors of the South Church in Boston, published a pamphlet entitled "Earthquakes the Works of God, and Tokens of His Just Displeasure; Being a Discourse on that Subject Wherein is given a particular Description of this *awful Event* of Providence. And among other Things is offered a Brief Account of the *natural, instrumental,* or *secondary Causes* of these operations in the Hands of God. After Which, Our Thoughts are led up to Him, as having the Highest and Principal *Agency* in this stupendous work. Made Public at this Time on Occasion of the late *Dreadful Earthquake* Which happened on the 18th of November

1755." His text was "God Shakes the Earth Because He is Wroth," based on Psalm 18:7: "Then the earth shook and trembled; the foundations also of the hills moved and were shaken, because he was wroth." In the Appendix, "Concerning the Operation of God in *Earthquakes* by Means of the *Electrical Substance*," he followed the customary practice of immediately applying current physical discoveries to all the world's unanswered problems and was one of the first authors to break with the Aristotelian tradition in the "boiling pot" theory of earthquake cause. "The sagacious Mr. Franklin, born and brought up in Boston, but now living in Philadelphia" had just made certain discoveries about the "electrical substance." Pastor Prince accordingly proposed that earthquakes were caused by an unbalance of electrical forces, particularly in cities such as Boston with many points of iron sticking into the sky.

On the occason of this same Boston earthquake of 1755, John Winthrop, Hollisian professor of mathematics and philosophy at Harvard College, also delivered and later printed a lecture reciting current theories of earthquake causation. They were in essence those of the Reverend Mr. Barnard in 1727, some but slightly modified from Aristotle in the fourth century B.C.

THE GENERAL PROBLEM

Pastor Prince and scientist Winthrop, in common with Aristotle himself and countless others of all ages, demonstrated strikingly the dangers of generalization and extrapolation from incomplete observation. You'll find the same thing in these pages when an attempt is made to summarize modern ideas about the ultimate forces that cause earthquakes. We have learned more of the laws governing the behavior of electricity and now know that potential differences of the kind pictured by the Reverend Mr. Prince cannot have a direct connection with

causing earthquakes. Geologists have learned that though fairly extensive caverns sometimes develop in limestone because of its solubility in ground waters, they are nothing like so extensive as Winthrop pictured them and do not exist at all in most of the rocks of the globe. And caverns of that type are never full of burning or combustible minerals or anything even remotely related to volcanic energy sources. But our own present attempts to extend known physical laws to unknown conditions at the depths where most earthquakes occur are subject to the same sort of future modification, and I shudder to think how they will sound to scientists a couple of hundred years from now. For that reason, any work on science, whether couched in differential equations and elliptic functions or reduced to words of six syllables, must be subjected to a constant sifting by its reader in order to keep observed facts clearly segregated from deductions based upon them. Even the "facts" need to be watched for overstatement, as witness Winthrop's assertion that natural scientists all agreed that "the earth is not solid throughout, but contains within it many large holes, pits, and caverns."

MODERN INFORMATION ON CAUSES AND EFFECTS OF EARTHQUAKES

The San Francisco Earthquake of 1906

At 12 minutes after five on the morning of Wednesday, Apr. 18, 1906, San Francisco, Calif., was shaken by a severe earthquake. A sharp tremor was followed by a jerky roll. The roar and crash of man-made structures mingled with a dull booming from the earth itself. Then, within about a minute, the shaking tapered off and the disturbance ceased.

A number of buildings were shaken into various stages of collapse. The new $7,000,000 City Hall was one of these. Many frame buildings were wrenched and distorted, some by the

slumping of loose soil under their foundations, but the damage to well-designed and solidly-built structures was less than generally realized. The 14-year-old 11-story Crocker Building, the steel-framed James Flood Building, the Mint, the new Post Office Building, the partially completed Hotel St. Francis, and scores of others escaped lightly. Authoritative estimates charge the earthquake's shaking with responsibility for less than 5 per cent of the total damage to property on that day. This was what is known as the San Francisco earthquake, one of history's most important.

Before people had gained the open air and begun to take stock of what had happened, puffs of smoke were mingling with the great cloud of dust that rose from the city. Realization of the full sweep of disaster was slow to come. The day wore on and people discussed their experiences. Some mourned their dead. All paused in momentary panic as repeated aftershocks swept under the city and on to the eastern horizon, but none of these matched the first great temblor, and gradually the tenseness of the populace eased. Then the significance of a growing pall of smoke down Market Street and over a widening area began to appear. There was insufficient pressure in the city water mains, which had been broken in many places. Ordinary means of combating conflagration failed. The fire was beyond control. Residents of the threatened districts began a trek to open spaces in outlying sections. Three days passed. By the dynamiting of structures in their path, flames were robbed of fuel. Finally, rain fell. Meanwhile crowds of refugees, huddled together without elementary sanitary precautions, were attacked by epidemics of filth-borne disease to cap a week's nightmare. This was the San Francisco fire, which occasioned property losses estimated at $400,000,000.

Total loss of life from this earthquake along the California coast probably did not exceed 700, approximately that occasioned by the New England hurricane of Sept. 21, 1938, or by

automobiles in the United States practically any week of a peacetime year.

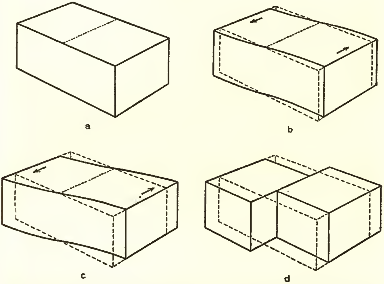
In reality, the earthquake didn't occur at San Francisco at all, and its historical importance does not rise from the fact that the new $7,000,000 City Hall and many other buildings were ruined or that a spectacular and disastrous fire followed. A couple of hundred miles of California's coast were shaken much more severely than San Francisco that morning. The earthquake's intensity has been exceeded many times elsewhere, and incomparably greater losses of life and property have resulted. The California, or so-called San Francisco, earthquake of 1906 stands as one of the world's most important because of the striking nature of clues to its cause which were left and of the thorough scientific investigation and report based upon it.

Tracing across California's coastal ranges of mountains for some 600 miles is a scar in the earth's crust, which geologists call a *fault*. It has been called the San Andreas Rift or San Andreas Fault. It is one of thousands, if not millions, which mark the globe's surface and are believed from indirect but strong evidence to crisscross the interior for many miles downward.

Along about 1800, all was peaceful and at rest along the northern part of the San Andreas Rift. Then, urged by internal forces which are constantly at work, the bordering land was gradually shoved and twisted until by 1875 the region along the fault was considerably warped. The shoving and bending continued until, on the morning of Apr. 18, 1906, the rocks were strained to the limit of their strength. At 5:12 A.M., they broke along a 200-mile section of the fault and snapped back into a nearly unstrained position. The resulting displacements were as great as 21 feet in places, and the vibrations set up by the violent adjustment traveled outward in all directions. At San Francisco, 10 miles from the nearest part of the fault, they were strong enough to be felt and to do damage. They coursed on

through and around the earth, gradually dying out, but with enough energy to leave records on seismographs, instruments designed to record such disturbances, on the other side of the world.

Fences and roads which crossed the fault were offset. A walk leading up to the steps of a ranch house near Olema hopped



Cause of the California earthquake of 1906. Schematic sketch of distortion along the San Andreas fault: (a) *undisturbed about 1800;* (b) *condition about 1875;* (c) *just before 5:12* A.M., *Apr. 10, 1906;* (d) *after the quake.*

northwestward several feet, while the house was displaced in the opposite direction. Water pipes crossing the fault were completely disrupted.

These, however, are rare phenomena. In no other earthquake on record has an equal length of fault displacement been traced. Effects more commonly associated with earthquakes are indi-

rect ones resulting from the vibrations that travel outward from the ruptured ground at the fault.

Japanese Earthquake of 1923

Facts of seismology as at present known justify at least one sweeping generalization: Never predict anything about earthquakes. This was dramatically demonstrated by a Japanese seismologist, Fusakichi Omori, in Tokyo. It was he who, at the start of a brilliant career in the science, made the historic study of the foreshocks and aftershocks of the Mino-Owari earthquake of 1891. As professor of seismology at Tokyo Imperial University, he watched closely the occurrence of minor shocks around Tokyo. When, on Wednesday, Apr. 26, 1922, a severe tremor shook the vicinity, causing some damage, he concluded that this was the principal shock of the series and announced, on the basis of that very reasonable deduction, that Tokyo probably need have no further fears of a major earthquake for a century or more. But that actually was only another foreshock preceding the greatest earthquake catastrophe of modern times, if not of all history.

A distinction, fine though it may sound, that needs to be made is between "prediction" in the sense of naming time and place, even negatively as Omori did, and "warning" in the sense of pointing out to large communities that they are within an active belt and should take steps to minimize the resultant dangers. Japanese seismologists, including Omori, had warned Tokyo for years that the water-supply system would not withstand even moderate shocks. As early as 1905, Imamura published in a journal called *Taiyo* his opinion that there was a possibility that Tokyo might be visited by a destructive earthquake in the near future and that it would be followed, if the water system and equipment for fire protection were not improved, by a general conflagration in the course of which 100,000 or

more lives might be lost. He documented his statements by reciting the history of previous earthquakes in Tokyo, pointing to destructive earthquakes elsewhere which had been followed by great fires, and pointing out that a statistical study of casualties in Japan showed one death for every eleven collapsed houses without fire and several times that ratio where a general outbreak of fire followed the quake.

One minute and twenty-eight seconds before noon on Sept. 1, 1923, snapping of the crust under Sagami Bay, 50 miles from Yokohama and 70 miles from Tokyo, produced vibrations which spread outward with such energy as to do serious damage within an area 90 miles long and 60 miles wide along the coast. Famed Mt. Fuji was within this zone. Some of the effects were described in Chapter 1.

A curious feature of the distribution of damage from vibration shaking was that many parts of Tokyo, 70 miles away, were more seriously affected than some of Yokohama, at 50 miles, and even places on the island of Oshima, less than 10 miles from the center of the disturbance. Similar observations were made at San Francisco in 1906. Investigation demonstrated that the effect on structures was greatly influenced by the nature of the ground under them. It showed that those on "made land," or water-soaked unconsolidated sand and silt, were shaken from five to ten times as severely as those on solid rock.

The fault that caused this earthquake has never been seen. Soundings of the sea bottom in Sagami Bay revealed great changes, but many could be accounted for as submarine landslides. The proximity of the active volcanoes Mihara, on the island of Oshima, and Fujiyama, on the mainland, led to speculations concerning the effect of this major crustal adjustment on possible future eruptions, but both remained singularly unaffected.

"Permanent" Changes of Land Level

Natives of the Land of the Rising Sun are sons of the rising land. The islands' frequent severe earthquakes are associated with the making of a range of mountains which are rearing their heads above the sea. Along the coast not far from Tokyo,

Cliff with record of changing land level in Japan. Location outside Yokohama is shown on page 32. Inset, portrait of Lithophaga nasuta, the historian. (After Imamura)

a record of this rise during historic time is to be found engraved in stone. In that region lives a certain boring bivalve known as *Lithophaga nasuta,* which occupies a cigar-shaped pair of shells a couple of inches in length and drills a home into the rocky shore at mean sea level. He lives on organisms brought to his door by the sea. At one place four different sets of these bore holes have been found at different levels. A bit of deduction based on historical records has attributed their present positions above sea level to elevations of the land which occurred

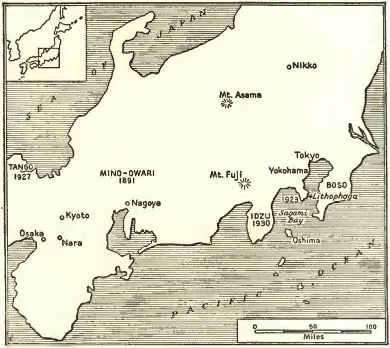
at the times of earthquakes in the years 33, 818, 1703, and 1923. The total uplift was 45 feet.

It takes a long time to make mountains at the rate of 45 feet in nineteen centuries, but geological processes have all the time in the world. Occasionally they work faster. In 1899, near Yakutat Bay, Alaska, a series of major shocks occurred. Investigators later found recently dead remains of sea animals on a wave-cut platform which was 50 feet above sea level. This elevation had been accomplished in a single jump, putting Alaska three jumps ahead of Japan.

Mobility of the Earth's Surface

The science of seismology has a record of advancing best over the ashes of catastrophe. Even in Japan, with an average of a destructive earthquake every three years, official and public interest in scientific study of the subject lagged progressively from 1891 to 1923. Following the Tokyo earthquake of 1923, however, interest, available funds, and activity spurted again and, with the aid of stimuli in 1927, 1930, and 1933, maintained a high level for some time. One manifestation of government interest was the running of extensive precise surveys to fix the horizontal position and the level, or vertical position, of closely spaced networks on the islands. An important outcome of this was the discovery that there the earth's crust is composed of a mosaic of blocks of irregular outline and up to five miles in greatest surface dimension. These are sometimes combined into groups ranging up to 30 miles across. The blocks roll and toss like ice cakes on a heaving sea, seemingly nearly independent of one another. Some are bounded by known faults, but all must be outlined by planes of weakness to permit such behavior. And under them must be seething forces constantly at work to produce an eternal restlessness. *This mobility of the earth's crust is the basic immediate cause of earthquakes.*

In spite of the history of seismic activity in the country as a whole, there are parts of Japan, particularly on the side away from the Pacific and bordering the Sea of Japan, where earthquakes are relatively infrequent. In 1925, the Tango Peninsula had no record of an earthquake since 1854. On Saturday, May

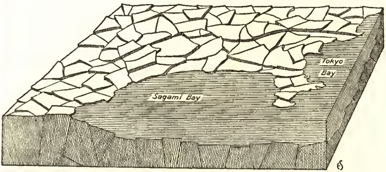


Location map for central Honshu, Japan, showing earthquakes of 1891, 1923, 1927, 1930.

23, 1925, a moderately destructive shock centered just west of the peninsula. It was followed on Monday, Mar. 7, 1927, by a severe shock at 35°36.′4 N., 134°58.′2 E., near what was known as the Gomura Fault Zone. About 3,000 persons were killed, and over 25,000 houses were completely or partially destroyed.

The staff of the Earthquake Research Institute went into

action immediately. Portable seismographs were set up for recording aftershocks; the geology of the region was studied; faults were located and mapped; structural reasons for the failure of houses were investigated; levels and triangulation surveys were run and re-run for comparison with previous surveys; the contour of the sea bottom was remapped by the Hydro-



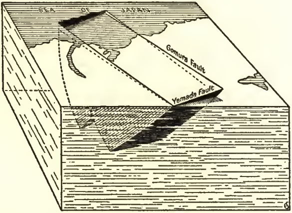
Schematic sketch of block structure of crust in Japan. Vertical scale greatly exaggerated.

graphic Department of the Imperial Japanese Navy. Correlation of all the data resulted in construction of the first complete picture in three dimensions of the form and size of a block the displacement of which caused an earthquake. As though squeezed beyond resistance, this block appeared to have cracked, popped up, and rotated, then made its final adjustments beginning at the bottom and working toward the surface until it had settled into a new position of temporary stability.

Frequency and Principal Zones of Occurrence of Earthquakes

The compilation of precise statistics concerning earthquakes is in its infancy. Only since 1918 has there been concerted international cooperation in exchange of information leading to the determination of locations of the largest ones from instru-

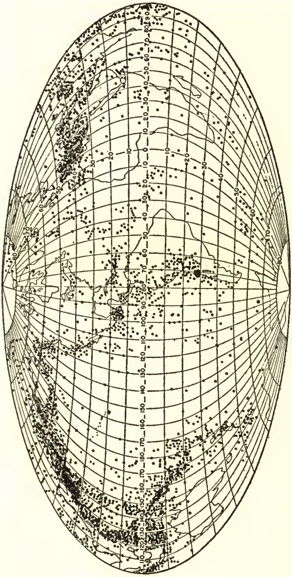
mental records. In that short time, the numbers of readings available for this purpose have tripled by reason of increase in number and improvement in quality of seismographic stations. As a partial result of this, the number of earthquakes located instrumentally each year has nearly doubled, though it is certain that the absolute seismicity of the globe has not done so.



Block that rotated and cracked to cause the earthquakes of 1927 on the Tango Peninsula, Japan. Vertical scale exaggerated.

Historical records show that a given region may undergo a spasm of activity followed by a lull of two or more centuries, yet our modern instrumental records cover only a quarter century. It is inevitable, therefore, that there are many seismic sections of the globe not represented in current statistics. This is confirmed by the fact that consistently about half of each year's locations are in places from which there was no previous instrumental record. In fact, there are probably not many, if any, square miles of the earth's surface which have not experienced and will not at some future date again experience earthquake vibrations strong enough to be felt or even do damage.

At the present time, instrumental records are being used to



Locations of 3,737 earthquakes that occurred during 30 years, from 1899 to 1910 and from 1913 to 1930, on Aitoff's equal area projection. Such a map stresses the importance of regions of relatively low seismicity at the expense of others such as Japan, because it gives no information about numbers of repetitions at active centers.

locate an average of from 600 to 700 earthquakes a year. Of these, from 50 to 100 may be literally world shakers capable of causing catastrophe if the luck of location placed a large center of population near at hand. In such matters, as illustrated at San Francisco, Tokyo, and throughout history, man is his own worst enemy in that it is his own devices that trap him, not the absolute fury of nature as in some other forms of catastrophe. If we wish to stretch the thing to some kind of limit by including everything down to the smallest trucklike tremors unrecorded in remote spots, following major earthquakes by the thousands as aftershocks, it is likely that a figure of 50,000 earthquakes per year is short of the true number rather than over, better than 150 per day. One seismologist's estimate reached 1,000,000 per year.

Of these, the majority in our current records tend to cluster in two zones. One of these borders the Pacific Ocean. The other starts in the Mediterranean basin and Central Europe, swinging easterly through Asia and southeasterly along the Malay Peninsula to join the first zone in the South Pacific. A minor zone traces along a buried ridge down the axis of the Atlantic Ocean. In point of numbers, perhaps 75 per cent of the world's earthquakes are now occurring in these zones.

PREDICTION

These details throw some light on the value of predictions of perennial prophets who discover in themselves an ability to foretell earthquakes. As recently as 1935, a resident of New York City achieved some publicity along those lines. Using a system involving planetary conjunctions, first tried unsuccessfully by Conrad of Megenburg in 1359, when it was based on Aristotle's theory of causation, he named a certain week within which there was to be "an earthquake in islands northeast of Australia." The approximate magnitude was not stated, but to

make this any kind of argument at all, we have to assume that a large one was meant; in the hundreds of thousands of square miles of active seismic region thus loosely designated, it is unlikely that a week has passed since the dawn of the present geological epoch without the occurrence of several hundreds of small ones. In spite of the latitude (and longitude) which the man allowed himself, he had the amazing misfortune to select one of a dozen or so weeks of the year when not even a moderately large shock was reported from the region. It did happen that the volcano Krakatoa belched during the week, a thousand miles in the wrong direction, and through some species of journalistic legerdemain, this was published as a fulfillment of the prophecy. Thereupon, dusty professors in highly endowed universities were called upon to blush that an amateur with globe and compass had penetrated the mysteries of earthquakes where their vaunted science and shiny (?) laboratories had failed for generations. Within a month, the prophet had slept undisturbed through the vibrations of a major, but unpredicted, shock in Canada which was felt as far south as Washington, D.C. He promptly did a private act of planetary conjunction popularly known as going into an eclipse.

Earthquakes, like so many things in nature, occur in cycles, but they are not regular enough to permit even a rough guess as to when another one is due. Tokyo, during the past 250 years, has had several severe earthquakes. There was a major one Dec. 31, 1703, and one of almost equal severity Oct. 28, 1707; 64 years later in April, 1771; 84 years later on Nov. 11, 1855; and 68 years later on Sept. 1, 1923. The 1703 and 1923 shocks were from practically the same source.

Northeastern America, though not in the principal zones of present activity, has a history of seismicity for which records of the past 300 years have been kept. They include a major earthquake at Boston in 1755, 192 years ago. Water-supply investigators have found evidence of a progressive tilting of the ground

resulting in subsidence of the land relative to sea level at the rate of one foot per century at Boston and about two-thirds that amount at New York. Geologically modern sea beaches are found 700 feet above present sea level near Montreal. The necessary restlessness of the crust appears to be present for the production of earthquakes.

A sweep of nine centuries is covered by records from Lisbon, Portugal, starting in 1009, culminating in one of the world's greatest known earthquakes on Nov. 1, 1755, and carrying through to today. The intensity of the earliest shocks is in doubt, but a major one in 1344 was followed 187 years later by a principal shock in 1531. This, in turn, was followed 224 years later by the shock of 1755. Each principal shock was preceded by foreshocks and followed by aftershocks. Some of the most severe of these were entered in the record. Aftershocks following the earthquake of 1755 practically ceased in 1858, since which time the region has been quiescent. Thus, in Lisbon and Boston, which had their most recent great earthquakes in the same month nearly two centuries ago, are two good candidates for a return to the active class within this century.

DEEP EARTHQUAKES

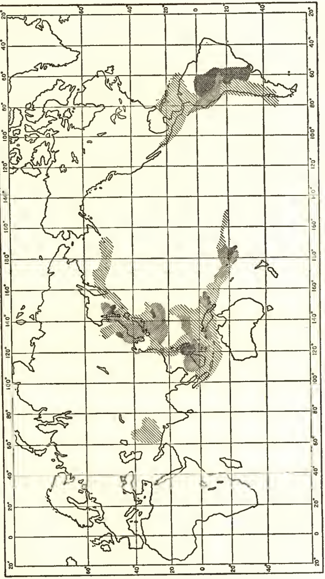
The San Andreas Fault displacements, changes of level near Tokyo and in Alaska, and similar cases supply significant evidence of the mechanism involved in snapping of the earth's crust to cause earthquakes. They represent a small percentage of the world's earthquakes, however, for the great majority leave no such obvious clues at the surface. The point at which a break begins, called the *focus,* seldom if ever right at the surface, is ordinarily from 10 to 30 miles deep. Vibrations from such a focus are called *normal,* or *shallow-focus,* earthquakes and constitute from 80 per cent to 90 per cent of recorded shocks as far as we now know. Scattered through the records of

modern seismograph stations, however, there were a few which differed radically from the general run of these normal earthquakes. Just a few years ago, an explanation for these was found, and they can now be interpreted. They come from foci which are deeper than normal. The deepest which have been observed to date were 700 kilometers (435 miles) below the surface of the earth, over a tenth of the way to the center. Maybe that doesn't sound like much, but scientifically it was an exciting discovery because before it was made there was believed to be no doubt, on theoretical grounds, that rocks at such depths could not have enough strength to accumulate stresses which, when suddenly relieved, would cause earthquakes.

The present distribution of these deep-focus earthquakes also is unique. One region in which they are fairly common is South America. There the deepest ones occur inland, shallower ones toward the coast, and the normal shocks nearest the coast and offshore. A depth of 650 kilometers (400 miles) is favored by the South American variety. Japan is another scene of deep-focus earthquakes. There, the favored depth is nearer 350 kilometers (220 miles). Others are relatively numerous in the South Pacific Ocean. An isolated group of 230 kilometers (140 miles) depth is located near the Pamir Plateau in the Hindu Kush Mountains of the Himalayan region.

Deep-focus earthquakes are bringing to light many new and interesting details of our earth-globe's restless surface. They appear to be outlining for us the important structural trends of some of the youngest of this geological era's crop of mountains and the deep-seated lines controlling present volcanic activity.

From a strictly practical standpoint, deep-focus earthquakes, often severe, are ordinarily felt over very large areas without doing serious damage at any particular place because there is no point on the surface close enough to feel the full effect of the vibrations at their strongest near the focus. A marginal case, representing a partial exception to this rule, was the disastrous



Zones in which deep focus earthquakes are occurring. Heaviest shading is over regions of deepest foci.

Earthquake Repetitions, 1918–30 within a Few Days of the Same Dates

Latitude	Longitude	Date
5°.5 S	145°.0 E	1926 Sept. 7 1928 Sept. 7
4°.0 S	144°.6 E	1918 June 10 1920 May 13 1929 June 12
0°.5 N	126°.5 E	1920 Dec. 18 1923 Dec. 19
6°.5 N	127°.0 E	1918 Feb. 7 1920 Feb. 25
33°.0 N	137°.5 E	1925 Apr. 19 1926 Apr. 1
36°.0 N	134°.0 E	1919 July 27 1926 July 26 1927 July 4
49°.7 N	154°.8 E	1929 Jan. 13 1930 Jan. 5
51°.0 N	179°.5 W	1918 Sept. 30 1920 Oct. 28 1921 Nov. 11 1923 Nov. 17

shock near Chillan, Chile, on Wednesday, Jan. 25, 1939, where 25,000 lost their lives and extensive property damage was caused by an earthquake which originated more than 70 kilometers (43 miles) below the surface. Another case, which received much attention in the newspapers, was a severe shock not far from Bucharest, Rumania, on Sunday, Nov. 10, 1940. Its proximity to some large oil fields led to widespread speculation on the possibility of its having ruined the fields' productivity upon which Hitler was counting at the time. Seismologists knew within a few hours of the quake's occurrence that this could not have been the case because the focus was computed from the records to have been 125 kilometers (78 miles) deep and vibrations from that distance could not seriously disturb oil-bearing structures near the surface.

A surprising number of deep foci have shown an as yet unexplained tendency to operate on or very near the same dates in different years. In sixty locations at which there was more than one shock between 1918 and 1930, there were twenty repetitions within a few days of the same dates. Some examples:

PHENOMENA ASSOCIATED WITH EARTHQUAKES

"The Earth Yawns Open!"

In Reverend Mr. Barnard's sermon was the passage, "by which the earth heaves up till it bursts, and swallows what is near it, in the gaping chasm. . . ."

In an otherwise authoritative and enjoyable popular modern book on earthquakes, several pictures of cracks in the ground were shown, and it was stated that "the cracks in some cases have opened and then closed under great pressure. The expression regarding the 'earth opening and swallowing' men or animals is derived from actual occurrences during earthquakes. Men and animals have fallen into crevices which then closed

before they could escape. In some cases the bodies have been brought to the surface along with ejected ground water and sand."

In a still more recent popular book on earthquakes appear pictures of cracks in the ground with no associated explanations. In a magazine published in January, 1941, an account of "America's Greatest Earthquake" (New Madrid, Mo., Dec. 16, 1811) included:

> Thousands of square miles of forest-grown expanse rose and fell under progressive rolling waves like an ocean lashed by a hurricane, cracking open in yawning chasms up to seventy feet wide. . . . Those not paralyzed with fright were frantically felling trees at transverse angles with the cavernous fissures running through the forest. . . . Many of the original craters and fissures closed at once after disgorging the varied substances from the earth's interior, but thousands of both yet remain, the fissures hundreds of feet long and up to fifty feet wide, with trees growing in their bottoms.

These are random samples of reports that are a perennial plague to unromantic seismologists. Built on a nucleus of truth, they are phrased and half told in such a way as to leave with trusting readers an impression supporting one of the most universally accepted misconceptions in the public's earthquake lore: that an awesome concomitant of catastrophic earthquakes is the yawning open of the solid earth in chasms that swallow houses, men, and animals, then close upon them again for all time.

The ground on which we live is a combination of rocks with earth, soil, or materials derived from rocks. The truly primitive rocks of the outermost crust were complex mixtures of many minerals solidified into crystalline units from a molten mix. Such rocks exposed at the surface undergo constant disintegration. Frost action breaks off pieces. Rain and ground water dissolve some of the minerals and weaken the bonds of others.

Fragments and dissolved constituents which result are transported to new places by wind and water. Since streams effect a large part of the transportation, the products of this erosion generally find their way into lakes, seas, or oceans, where they settle and remain. Solid particles form mechanical deposits such as gravel, sand, and clay. These, when compacted and cemented together again, form rocks known as conglomerate, sandstone, and shale. Materials transported in solution, if deposited through the aid or under the influence of animals or plants, form organic sediments; if precipitated without the aid of living organisms, chemical deposits. Rocks of organic and chemical origin are limestone, gypsum, salt, iron ore, peat, lignite, and coal. The various kinds may be deposited singly or in many combinations, producing a great variety of rocks.They all constitute a general class known as *sedimentary rocks*, as contrasted to the original combinations which crystallized from melts as *igneous rocks*. Either of these may be so altered by heat or pressure that they lose many of their original characteristics and become hybrid forms known as *metamorphic rocks*.

Rocks of all these classes form the foundation of our continents today, but resting on them over large areas are unconsolidated masses of gravel, sand, clay, and soil. Such masses occasionally become unstable on slopes and slump or slide into new positions. Earthquakes are caused by breaks in solid rocks of the crust, sometimes far below the surface, sometimes near or at the surface. These breaks invariably result from pressures which shove great blocks about, but always work to push them against each other. They cannot, *and never do*, pull them apart to leave yawning chasms in the solid crust. Sometimes, however, the shaking that results when crustal breaks occur jars masses of unconsolidated materials so that they slump or slide into new positions. The natural cracks and fissures that result in such deposits are no more fearful or remarkable than they would have been had the slump or slide occurred after a hard

rain. Maybe this sounds like begging the question, but the point is to emphasize these indirect effects of earthquakes as really normal, familiar processes and get away from what seems to be a popular tendency to dramatize them under the special conditions when earthquakes instead of heavy rains pull the trigger.

On the very rare occasions when the rock break that produces an earthquake comes right up to the surface of the rock crust, special effects may be produced in any unconsolidated sediments which blanket that rock. They represent a relatively paper-thin sheet glued by their weight to the underlying rock and naturally tear and crumple slightly when their rock base shifts. A detailed study of such tears and crumples in the Cedar Mountain, Nev., earthquake of Dec. 20, 1932, showed that the resulting fissures did not exceed a few inches in opening and depth.

Shifts in the unconsolidated dirt and soil mantle of a severely shaken region near the source of an earthquake also sometimes derange ground-water circulation and affect wells, or force jets of water out of the ground in such a way that they form craterlets or ridges of sand. In the Japanese earthquake of Sept. 1, 1923, a special case of cracks opening and then squeezing shut was reported. They occurred where an old mucky rice field had been removed from cultivation and covered by a layer of relatively dry loam. Waves set up by the earthquake sloshed back and forth in the muck of the old rice field, and as they passed certain places the loam cover arched and cracked open slightly, then settled back and closed up as some of the rice-field muck squeezed up through the temporary opening.

The "yawning chasms" of the New Madrid earthquakes of 1811, as well as the numerous landslides and new lakes, all resulted from slumps, slides, and the general effects of severe shaking upon unconsolidated alluvial deposits in the region.

In contrast to permanent fissures in unconsolidated ground,

caused by slumps and slides, there have in the past been tales of the ground's opening to swallow people, even villages, and closing with no trace of the opening remaining. An examination of the record on this subject shows such reports to be curiously concentrated in the relatively remote past. After an earthquake at Riobamba, Ecuador, on Feb. 4, 1797, reports came out of men buried to their waists when the ground opened under them and closed upon them. Geologist Sir Charles Lyell, in gathering reports of effects of an earthquake at Jamaica, British West Indies, June 7, 1692, wrote:

> It is said that the ground swelled and heaved like a rolling sea, and was traversed by numerous cracks, 200 or 300 of which were often seen at a time, opening and then closing rapidly again. Many people were swallowed up in these rents; some the earth caught by the middle and squeezed to death; the head of others only appeared above the ground; and some were first engulfed and then cast up again with great quantities of water.

In a *History and Philosophy of Earthquakes from the Remotest to the Present Times,* edited by a member of the Royal Academy in Berlin in 1756, some effects of the Lisbon earthquake of Nov. 1, 1755, at Algiers and Morocco across the Strait of Gibraltar, were said to have been:

> By the falling down of a great number of houses, many people lost their lives; and about eight leagues from this city, the earth opened and swallowed up a village, with all its inhabitants (who were known by the name of the Sons of Busunba) to the number of about eight or ten thousand people, together with their cattle of all sorts, as camels, horses, horned beasts, etc., and soon after the earth closed again in the same manner as it was before.

The Calabrian earthquake near the toe of the Italian boot, Feb. 5, 1783, caused an unusual number of landslides and slumps in unconsolidated material. Sir Charles Lyell again preserved for the record hearsay accounts like:

According to the Academicians, who investigated the present earthquake, when deep abysses had opened in the argillaceous strata of Terra Nuova, and houses had sunk into them, the sides of the chasms closed with such violence that on excavating afterwards to recover articles of value, the workmen found the contents and detached parts of the buildings jammed together so as to become one compact mass.

These accounts are typical of the colorful but unsubstantiated tales current in a day when hysterical mysticism had not been replaced by careful observation. In the final official report on the California earthquake of Apr. 18, 1906, is an isolated passage: "In this connection mention may be made of the fact that at the Shafter ranch (near Olema) a fault crevice was momentarily so wide as to admit a cow, which fell in head first and was thus entombed. The closure which immediately followed left only the tail visible." Even if the tale is aboveboard, it is incomplete, for a simple explanation like that of the Japanese rice field would undoubtedly have rewarded detailed inquiry. Akitsune Imamura, former professor of seismology in Tokyo Imperial University and a leading Japanese seismologist, stated in 1936 that belief in the earth's man-swallowing propensities was widespread in his country. He attributed this in part to an allusion in one of the Buddhistic sutras "where it is mentioned that when Devadatta, one of Sakya Muni's disciples, turned against his Master and even made attempts on his life, Heaven punished him by consigning him to Hades whereupon the ground opened and immediately swallowed him. Upon seeing this, it is further written, a disciple of the delinquent went to his rescue, but without avail."

An example of what unchecked rumor can do in perpetuating unfounded stories occurred following two strong earthquakes in New Hampshire on Friday, Dec. 20, and Tuesday, Dec. 24, 1940. Newspapers and radio speed the spread, but the principle is the same. Someone observed that the level of Lake Ossipee

was approximately a foot lower than it had been before the quakes, and speculation became rife about chasms in the lake bottom which would drain it and leave cottages on a lakeside with no lake. It later developed that a power company dam at Effingham Falls had been opened for a short time, for reasons

Cracks in pavement after earthquake vibrations had caused underlying loose material to slump toward canal, in Japan, 1923. Such pictures are used to frighten children, but don't prove that the earth yawns open.

not connected with the earthquake, and when it was closed the lake recovered its normal level without further ado. Still, for one person who read the explanation, I meet ten who heard only the rumor, and it's a fair bet that the original story will crop up for years to come. Those things die hard. In an earlier day, they survived and grew.

Japan is as complete a laboratory as the world has for demonstrating the whole gamut of earthquake effects, yet Imamura says of it: "As no authentic record exists in this country of an open fissure having closed up and engulfed men and animals,

this dread of fissures finds no justification so far as records of Japanese earthquakes are concerned." He adds, quietly but firmly, ". . . seeing that no examples have been recorded for the nineteenth and present centuries, one may be excused for questioning their verity."

The effects of an earthquake's severe shaking upon a given area of unconsolidated material can be predicted in advance of any quake, and one thing people in seismic zones most certainly need not worry about is a mysterious, uncanny opening of bottomless cracks in the solid rocks of the earth under their feet, which will swallow them and then close again.

Earthquake Sounds

An earthquake is a vibration in the ground. Sound is a vibration in the air which produces a familiar effect on our eardrums. Philosophers are reported to have been exercised over whether a sound exists if there is nobody around to hear it. It does. It is alternating compressions and rarefactions of the air, which travel outward from a source as waves. If these occur 435 times a second, we hear a note called "middle A." If they are irregular and jumbled, we hear a noise which may be low and booming or high and shrill, depending on the proportion of slow or rapid compressions in the jumble. If they are sufficiently irregular and jumbled, they are called "swing."

During an earthquake, there are frequently vibrations in the ground which disturb the air in such a way as to produce sounds within the range of the human ear's receiving band. These are *earthquake sounds*. They have been variously described, usually on the low booming side of the scale. Very near the source of an earthquake, the sounds sometimes include sharp snaps and suggest the tearing apart of great blocks of rock. Farther away, they have been likened to heavy vehicles passing rapidly over hard ground or a road; dragging of heavy boxes or furni-

ture over the floor; a loud but distant clap of thunder; an explosion, or the boom of a distant cannon; the fall of heavy bodies, or loads of stone or coal falling. Winter quakes in New England combine sound and shaking in a way that suggests almost simultaneously to thousands of householders that something has happened to the oil burner or the steam boiler.

Earthquakes are accompanied by sound in a very large number of cases, if not in all. As a rule, the beginning of the sound precedes that of the felt shock, the loudest sound accompanies the greatest shaking, and the end of the sound coincides with the end of the shaking. There are many exceptions, but it is difficult to assemble reliable statistics on a phenomenon of this kind. Anyone who has experienced a severe or even moderate earthquake knows that the confused impressions that result are so mingled as to render uncertain subsequent attempts to untangle and specify them.

The statement has been made frequently that the sound was heard approaching from a distance, or a definite impression of direction to the source was registered. Professor Winthrop stated:

> The motion of the earth in this instance plainly appeared undulatory to me; and this shock, I apprehend, was occasioned by one small *wave of earth* rolling along, but not with a very swift motion. For the velocity of its progress was considerably less than that of sound, which moves about 13 miles in a minute; as appeared from hence, that the roar of this earthquake might be heard at least half a minute before the shake was felt.

If his statement about the relative velocity of sound in air and earthquake waves in the ground were true, it would be easy to understand hearing the sound approach from the direction of the source. The awkward part of it is, however, that all the principal waves travel much faster in the ground than sound travels in air. The fastest average roughly 220 miles per minute;

the ones which cause the greatest shaking, about 125 miles per minute; and the slowest surface waves, just a little less than that. Thus the earth waves which are sources for the sound in the air reach an observer long before their airborne derivatives could get there from points in the line of approach. This difficulty is not connected with hearing the sound before feeling the shaking, because the sound waves travel more than 1½ times as fast in the ground as do the shake waves which are often the first to be felt, especially at a distance from the source.

Gunfire Earthquakes

Under special conditions, the sound of distant gunfire has been mistaken for an earthquake. An unusual example of this on the night of Jan. 27–28, 1930, was investigated in detail by California seismologists after they had received a number of reports of earthquakes that were not recorded on seismographs. The United States Coast and Geodetic Survey received such reports as:

LOS ANGELES. A succession of sounds after midnight, no rattling.

LINDSAY, PORTERVILLE. Shock felt at 12:23 A.M.

Five miles east of Bakersfield. Nine quakes at intervals of ½ minute, each 20 seconds long, felt by few, slow motion, beginning gradual, rattling of windows and doors, doors swung, at 12:23½ A.M.

BAKERSFIELD, 12:23½ A.M. (*press report*). Police received twelve calls for help against supposed burglars. Doors and windows shaken, dull roar resembling a distant blast; not felt; lasting over about 3 minutes; observed east, south, and west of Bakersfield. At Stockdale, windows and doors shaken, curtains moved outward, hanging lights swung, no movements of buildings.

PASADENA, 12:25 A.M. (*press report*). Thirty calls to police, believed to be an earthquake; rattling of doors and windows, lasting more than 30 seconds.

ARCADIA, 12:26 A.M. Four shocks, motion same as heavy swell, shock plainly heard as it approached and before it was felt, lasting ½ minute; felt by many; slow, beginning gradual, rattling of walls, frame; awakened many, frightened few.

It developed that a battleship commenced firing in target practice at 12:10:53 A.M. and ceased firing at 12:15:00 that night. The ship was 70 miles offshore, and the distance to the point of the strongest effect, near Bakersfield, was in the vicinity of 150 miles. This was an example of the abnormal audibility of gunfire, which had been observed many times in Europe, where they have more opportunities for that sort of thing. It is due to the sound's following a curved path in the upper air, skipping intermediate points, and reaching distant surface points with enough energy to simulate a small earthquake in sound effects on buildings.

Flashes of Fire

In reports of the Bucharest earthquake of 1940, another ghost arose to plague seismologists. One account included the striking statement that "the blackout of Bucharest was illuminated by the flash of blue fire which accompanies the first waves of earthquakes." That is a gross libel on earthquake waves. For centuries, claims of fire flashes seen at the time of earthquakes have appeared from place to place. Without exception, the only ones subject to any kind of investigation have been found to be due to indirect effects such as electrical short circuits, or completely independent phenomena such as lightning from thunderstorms in progress at the same time, or meteors from scheduled showers of those space visitors. Earthquake waves themselves are in no way connected with light.

An unusual example of luminous phenomena truly associated with an earthquake, though again indirectly, was observed following a submarine shock off northern Japan, Friday, Mar.

3, 1933. Investigators concluded that the light at sea reported by many people from widely scattered points was caused by an advancing "tidal wave" disturbing myriads of *Noctiluca*, luminous plankton swarming in the offshore waters at the time. One of the investigators canvassed the evidence from A.D. 869 and found several cases of a wave reported advancing with a luminous crest. He suggested the phenomenon as a form of "tidal wave" warning on that coast and concluded seriously: "This is a problem which cannot be made light of from this point of view."

Landslides

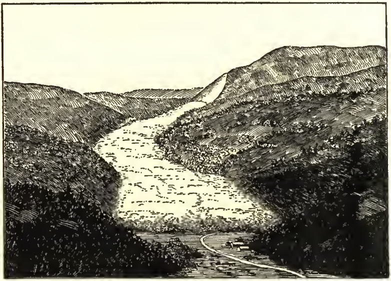
In regions of considerable relief, landslides are a frequent concomitant of earthquakes. They are usually of two main types: the simple slump and the avalanche, or rock flood.

Examples of each type converged in a spectacular manner on the village of Nebukawa, Japan, on the shores of Sagami Bay at the time of the Tokyo earthquake of 1923. At the instant of the shock, just before noon, a southbound train was standing at the Nebukawa station awaiting a northbound train which was to pass it at noon. The ground for a hundred yards on either side of the station broke away from the steep slope to which it had clung, and catapulted the train into the ocean. A couple of hundred passengers were reported drowned. This slump, with the underlying material moving out first, dropped an entire tangerine grove onto the former site of the railroad station in such a manner that, though a few trees leaned crazily, most of them continued to thrive as though nothing had happened.

The northbound train's engine had just emerged from a tunnel across a valley from the station as the shock dislodged a small slide which buried the engine. The interior of the tunnel was undamaged, as were the interiors of all tunnels in the dis-

trict, and the coaches were unharmed. Passengers clambered out as quickly as possible, and a few unfortunates walked onto the 120-foot bridge leading from the tunnel across the valley to the station.

Meanwhile, the shock had dislodged a rock avalanche of tremendous proportions on the peak of Mt. Hiziridake, 3,000 feet



Rock avalanche in Japan, 1923. Similar to the Nebukawa avalanche but of less volume and extent.

high and a little over 4 miles inland. Witnesses among the few villagers who happened to run in the right direction at the time reported that their first warning of this new peril was an ominous roar from inland. Then in a time which required a mile-a-minute speed, a wall of dirt and boulders swept into view and carried the 4-span bridge, with most of the remaining houses, into the sea. The speed and volume of this slide were attested by the manner in which it deposited material along the valley

walls to heights of over a hundred feet as it rounded curves in its course.

Extensive landslides do not ordinarily occur at distances over 20 to 30 miles from a major earthquake, though there have been some up to 50 miles from the very largest quakes' centers. On Sunday, Aug. 4, and Thursday, Aug. 8, 1946, two very strong earthquakes of a remarkable series of shocks occurred near 19.3° N., 69.0° W., just off the coast of the Samana Peninsula in the Dominican Republic. These caused slides on some steep rocky cliffs along the north coast of Samana Peninsula, but none along the east end of the peninsula or in Samana Bay. The slides were at 69°38′ W. and from 69°17′ W. to 69°21′ W. These same quakes generated moderate tidal waves, and all of this and previous series produced special groups of earth waves at seismograph stations in New England, which are being investigated with considerable interest. The region nearest the epicenter has few inhabitants, so damage to structures was relatively slight and there was no known loss of life, yet the quakes themselves were nearly as violent as the largest ever known to occur.

Floods of a different sort followed the Alaskan earthquakes of 1899 which elevated the seashore near Yakutat Bay 50 feet (see page 31). The severe shaking jarred great slides of snow from mountainsides onto the gathering grounds of glaciers in the vicinity. The impulse from this sudden abnormal increase in supply of materials coursed downstream through one glacier, which was carefully studied, at the rate of 3 miles per year. Seven years after the earthquakes the glacier suddenly came alive at its lower end and advanced hundreds of yards in a few months, where it had been stagnant before, as the glacier flood reached its terminus.

Landslides, whether caused by earthquakes or not, sometimes dam streams and cause the formation of lakes. A stream faced by such an obstruction usually finds a way through or

around it eventually, and the impounded water is released as a destructive flood when the dam collapses. A deceptive feature of this process is that years may elapse between the landslide and the flood. During that time people may settle below the "natural" dam or remain there on the assumption that the dammed lake is a permanent addition to the local scene.

In the deposits of loess, a fine-grained, wind-blown deposit, of the province of Kansu, China, an earthquake on Thursday, Dec. 16, 1920, caused some of the most spectacular landslide phenomena on record and a death toll of 100,000. Great masses moved over a mile, some carrying roads, trees, and houses undamaged. A popular description of the scene aptly called it the place "Where the Mountains Walked."

Earthquake Warnings

As we have already seen, earthquakes cannot be predicted in any precise sense of the word. On the other hand, the future does not always lie behind an impenetrable iron curtain, and warnings of a sort are available to certain regions.

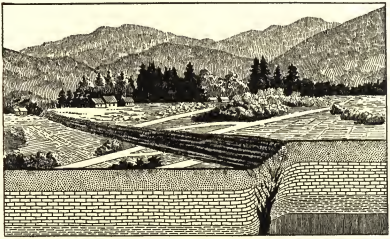
The progressive warping of the ground along the San Andreas Fault prior to the earthquake of 1906 was described in part from surveys which actually measured it and in part from deduction. The thought occurs at once that if such movements are continuing, as there is every reason to believe they are, careful observation should make it possible to determine when the next break will occur. Precise triangulation surveys have been established with the idea that repetition of them from time to time will supply a check on conditions. One obvious problem is to select reference points for such a survey which can be regarded as fixed. This cannot be done, but it is possible that motion along the San Andreas Fault is sufficiently more rapid than that in adjacent regions, so that the relative displacement of 20 feet observed in 1906 can be detected before fracture

occurs again. There remains, however, uncertainty as to whether fracture will take place again under exactly the same conditions of strain or whether the next time it may come when displacements are 15 feet, or 25 feet. *It is possible that something practicable can be worked out along those lines leading to prediction of earthquakes along the San Andreas Fault,* within the next thousand years. Even then, the time of occurrence may not be predictable more closely than ten, twenty or more years, and rules discovered there will not be likely to apply elsewhere.

Another form of warning is sometimes issued by nature where a major earthquake is being prepared. It consists of increasingly numerous small shocks as the strains become great. These are called *foreshocks*—but only after a severe earthquake has occurred and a dozen or score of years have elapsed to allow reasonable certainty that it was really the *principal shock.* Thousands of small disturbances which follow the principal shock for many years, as the displaced blocks of crust settle into their final positions before starting a new cycle, are called *aftershocks.*

This sequence of foreshocks, principal shock, and aftershocks sounds very systematic, even though it is not usually recognized until after the main event, and is well developed only for shallow earthquakes. In the vicinity of the Neo Valley section north of the city of Nagoya, Japan, occasional small earthquakes were not unusual in the middle of the nineteenth century. From 1885 to 1889, however, one part of that region was shaken five times as frequently as adjacent parts. During 1890 and part of 1891, the average frequency of earthquakes in that zone became ten times as great as elsewhere thereabouts, and the centers of the shocks clustered around a definite surface line running NNW–SSE, the Neo Valley Fault. On Wednesday, Oct. 28, 1891, land lying to the westward popped up from 3 to 6 feet relative to that on the east and slid

south-southeast about the same amount, though in many places as much as 20 feet. Vibrations from this rupture constituted what became known as the Mino-Owari earthquake because their shaking was greatest in the two provinces so named. Official tabulations listed the killed at 7,279, injured 17,393, houses entirely destroyed 197,530, half destroyed 78,296, burned 445,



Section of Neo Valley fault, Japan. Displacements along this fault produced many foreshocks, the Mino-Owari earthquake of 1891, and many aftershocks. (After Sieberg)

shattered and burned 5,934. The nearest seismograph, at Gifu, capital of the province of Mino, was buried by the collapse of the building housing it. Seven hours after the earthquake, however, it was put into working order and registration of the numerous aftershocks was begun. From that time until the end of December, 1893, that is, within about two years and two months, the total number of aftershocks recorded was 3,365. Of these, 10 were violent, 97 strong, 1,808 weak, and 1,041 feeble, while the remaining 409 were merely earthquake sounds unaccompanied by any perceptible tremors. It was computed

that, allowing for interruptions in the sequence caused by these strong aftershocks, the decreasing frequency of occurrence indicated a return to normal stability for that region, that is, an annual number of fifteen earthquakes, after the lapse of nearly forty years. By that time, the total number of aftershocks would have been 4,000, of which 720 came in the three days after the earthquake, 1,087 in November, and 416 in December, for a total of 2,223 in the two months and three days immediately following the principal shock.

In addition to the decline in frequency represented by these numbers, there was at the same time a rapid though fluctuating decrease in strength. Of the ten violent shocks recorded at Gifu, nine occurred within the first four months, and the last in September, 1892, seven months later.

Seismologists have learned that these aftershocks are characteristic of quakes which originate near the surface, or actually cause surface faulting as in Japan in 1891, but are far less numerous as the depth of the origin becomes greater. Sources as deep as 420 miles are known. Sometimes the major quakes of an entire province will show a tendency toward similar foreshock and aftershock habits. In northeastern America, for instance, several large quakes in recent years have been preceded by few or no foreshocks and followed by surprisingly few aftershocks. There were eight in the first month after the two December, 1940, quakes in New Hampshire, a total of twelve by the following February, and none thereafter.

The public often receives misleading impressions on the aftershock question. One of the first queries aimed at seismologists after a large earthquake has been felt over a wide area is, "Will there be more?" On the basis of normal experience, it is natural to answer, "Certainly, some aftershocks may be expected." Newspapers, with the need for compressing everything into a headline or attention-gripping lead are prone to report such a reply as "Seismologist predicts more quakes." For

the majority who felt the main shock, this "prediction" is never realized because the aftershocks are generally felt only near the source. Or if, as happened in the New Hampshire quakes' aftermath, a misguided seismologist tries to explain that owing to the probable depth of the source and habits shown by other New England quakes, it is unlikely that there will be many aftershocks (in the sense of Japan's thousands in the first few months), this is condensed to "Seismologist predicts no more quakes." A single one large enough to be felt over a considerable area (as happened here for the first time in history, four days after the first one) makes him a liar, by this headline, and even the smallest of the handful of aftershocks that inevitably follow makes him a liar to the residents near the source, who feel them all.

Since the first instrumental records of earthquakes were not made until the late nineteenth century, and even today scarcely a handful of the world's 300-odd seismograph stations have instruments of optimum sensitivity, we naturally have a very limited body of statistics on such matters.

Foreshocks are less likely than precise triangulation surveys to predict the time of a large earthquake with any useful accuracy. They may much sooner, however, be utilized as indicators of the probable places in which large shocks will occur. To cite San Francisco once more, only because we understand its situation better than most, the foot of Market Street is about midway between the San Andreas Fault, which produced the 1906 earthquake, and the Hayward Fault, along the western boundary of the Berkeley Hills, which caused a severe earthquake on Wednesday, Oct. 21, 1868. An idea of the present activity in the region is furnished by seismograph stations nearby which regularly map the locations of earthquakes along these faults and others. There are scores of other known faults in that and every region of any continent that has been studied in detail, but they are temporarily classed as "dead" until they achieve

the distinction of making news by causing an earthquake. Since it is unsafe to say that any "dead" one is not just resting, geologists often recommend caution in placing large structures on or too near a fault of any kind. When we are unable even to name the century in which danger may become acute, structural engineers, not without reason, are reluctant to let caution of that type cost too much in money or inconvenience by special construction or relocation. An argument along these general lines was reported to have delayed but not prevented location and construction of the Golden Gate Bridge, completed in 1937.

The danger to sound structures near or even on an active fault may easily be exaggerated. One of the water-supply storage reservoirs for San Francisco in 1906 was the Crystal Springs Reservoir, which lay right on the San Andreas Fault, filling a depression created by previous activity there. At the time of the 1906 earthquake, the earth-filled Upper Crystal Springs dam was apparently uninjured in spite of the fact that the fault traversed the rock forming the east abutment, in which an offset of 8 feet occurred. The 145-foot high concrete Crystal Springs main dam was not even cracked. Other dams held equally well, and there appeared to have been no leakage or drainage of the main storage reservoir basins on the San Francisco Peninsula. Disruption of the water supply occurred largely through breakage of main transmission pipe lines crossing the fault or laid on marshland, and through building service pipes which broke by the thousands and poured waste water onto the ground with consequent reduction of pressure needed for fire fighting. One report stated: "The total number of the house, hotel, elevator, standpipe, and factory connections, and of automatic sprinkler pipes thus torn off and left open by and during the entire conflagration, amounts to over 23,200 separate pipes in the burnt district."

The present reservoir distribution system of San Francisco

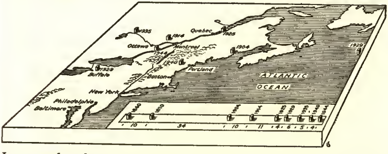
is specifically designed to avoid repetition of the failures of 1906. Principal transmission lines which cross dangerous territory are duplicated by others which follow widely separated courses; many gate valves are so placed as to permit isolation of broken sections and maintenance of pressure in the balance; an entirely independent auxiliary high-pressure fire system has been installed and may be supplied from a separate reservoir or even by sea water from a remote steam-driven pumping station; supplementing this high-pressure system is a series of underground cisterns scattered throughout the city. Residents of the present city of San Francisco may rest in the assurance that they are guarded by every device available to the earthquake-conscious engineers of their Water Department and Public Utilities Commission.

Famous Boulder Dam, across the Colorado River below the Grand Canyon, has an earthquake problem. A great many small earthquakes are felt in the vicinity and have been attributed to readjustments in the crust necessitated by the load of water backed up by the dam. Three seismograph stations have been established at the dam, and others are being planned. Their purpose will be to locate the sources of the shocks, of which there were 143 during 1937. Most of these occurred after March, when the dam's lake level began a rise which carried it from 1,020 feet to 1,100 feet above sea level.

Earthquake Hazard in New England

Without particular regard to the intensity of the shocks, the presence of earthquakes of any kind near spectacularly large cities like London, Tokyo, New York, Chicago, and Boston is intriguing. All these cities have had them, Chicago as recently as Saturday, Feb. 12, 1938, and New York several times within a little over a year in 1937–38. On Sunday, July 18, 1937, a quake originated on Long Island within 15 miles of Times

Square and shook 1,500 square miles of adjacent land perceptibly. There were several subsequent slight shocks in the vicinity; then on Friday, July 29, and Tuesday, Aug. 2, 1938, slightly larger ones in Westchester County to the north; on Monday–Tuesday, Aug. 22–23, 1938, three relatively strong ones and three weaker ones to the south in New Jersey on the same night, followed by one on Saturday, Aug. 27.



Large earthquakes in northeastern America since 1904, and time scale showing increasing seismicity in the region.

This minor activity is part of a general picture which leads this writer, at least, to the opinion that the seismic province embracing New England and adjacent sections of northeastern America is in an epoch of increasing seismicity which probably has not yet passed a climax. The intervals between larger shocks have been decreasing. A century of comparative calm followed the Boston earthquake of 1755; then in 1860 an earthquake in Canada was felt over an estimated 700,000 square miles (nearly double that of the San Francisco quake of 1906). In 1870 another Canadian shock was felt over a million square miles. Thirty-four years later, in 1904, came a strong quake in southeastern Maine. There followed another Canadian shock in 1914, and on Saturday, Feb. 25, 1925, a quake in the St. Lawrence Valley was felt over two million square miles, which places it definitely in the top brackets for absolute intensity.

Then the stronger shocks began to come still more closely together: Attica, N. Y., and off the Grand Banks, in 1929; Timiskaming, Canada, 1935; Saguenay River, Canada, 1929; two, four days apart, in the White Mountains south of Mt. Chocorua, N. H., late in 1940; and one near Cornwall, Ontario, on the St. Lawrence in September, 1944, doing damage estimated between $100,000 and $1,000,000. This reduction of interval between stronger shocks from approximately thirty to ten to five years, with minor activity meanwhile stepping up over the entire area, is what is meant by entering an epoch of increasing seismicity. There is absolutely no way of knowing that there will be so much as a single quake more in the next century, but experience in New England and other parts of the world indicates the strong probability that there will be more, some strong, and some in the central and southern parts of the district.

From an analysis of the past geological history, certain major divisions of the area have been identified. One boundary follows the St. Lawrence River for some distance and includes many of the Canadian shocks. Another traces just inland from and, for a way, parallel to the Bay of Fundy and the coast southwest of it. Another follows the trend of Lake Champlain. These are ancient scars from former epochs of mountain making, along which the present crust appears to be most ready to yield to the deforming forces now acting upon it. Details around the Boston basin have shown that it lies at an angle where major structural trends bend from a northward to a northeastward direction, near the focus of great forces which tore and snapped the rocks that to this day carry the old fault scars. Similar planes of probable weakness are known around New York City, through Connecticut, and elsewhere in New England. Along some such old planes of weakness, extending downward to great depths, it is most probable that the crust

blocks of the present will yield to the steady, enduring shoving from below.

As the writer summed up these observations for the *Harvard Alumni Bulletin* of Jan. 11, 1941:

> The situation puts seismologists on the horns of an old dilemma. The evidence is strong enough to warrant posting a warning to eastern seaboard communities, yet it seems to be impossible to issue such a warning without being misunderstood. It cannot be fairly condensed into a sentence or a headline. If the risk of a Portland, or a Boston, or a New Haven, or a Bridgeport, or a New York earthquake within the next fifty years is no more than one or two chances in ten, still it is there. If it doesn't materialize, the cry will be "wolf, wolf." But that seems to be a small penalty to a struggling seismologist as compared with "Why weren't we warned?" if one does come. So you may consider the warning issued.

For the record, it should be added that the above analysis of New England's earthquake past, present, and future is not accepted by all seismologists. One dissenter has been assuring the public recently through New York newspaper and magazine interviews that there is nothing to worry about. He reasons from the fact that no major mountain making is going on in northeastern America as it is in Japan, California, and other "earthquake countries"; therefore, "it can't happen here." He favors crustal recoil following the melting of ice-age glaciers as the cause of New England's shocks, which must perforce be minor "stair-creaking" phenomena, analogous to the recovery of a stair tread from the pressure of a footstep sometimes long after the pressure is removed.

This sort of negative prediction is as insidious as it is fallacious. In the tradition of Aristotle, the conclusions are faultless —if the premises are correct. Without regard to purely theoretical guesses as to the causal mechanism, it is known statistically that earthquakes of no mean magnitude have been

included in past as well as current New England cycles. Furthermore, the New Hampshire quakes of Dec. 20 and 24, 1940, originated at a depth of 20 miles, and others in northeastern America may have been even deeper. That looks to this observer like getting down into the foundations of things and out of any superficial "stair-creaking" class. There are deep-seated forces at work in that zone which give evidence of ample energy for destructive effects on any large community which has the misfortune to be located near the point at which it is released. Finally, that "it can't happen here" because mountains aren't being made here today is anachronistic anodyne, seismologically speaking. In 1811, the greatest quake known on this continent occurred in the Mississippi Valley south of St. Louis, and in 1886, one strong enough to be felt in Boston, 1,000 miles away, occurred in Charleston, S. C. The latter is about as far from geologically young, modern mountains as you can get on this continent, and the former is far enough to leave no doubt about the absence of connection.

Earthquake Precautions for Large Cities

Nothing that has been said should be interpreted to mean that residents of large cities in northeastern America, any more than California, or Japan, or any earthquake country, need simply resign themselves to the inevitable, in the death-and-taxes tradition. Something has already been said of steps taken to prevent a repetition of the San Francisco fire. There lie the first requirements for quakeproofing any city. Fire is a specific hazard (95 per cent of the total in San Francisco and Tokyo-Yokohama) which can be guarded against, and every large city should at least lay plans for action in an emergency. London and Chicago can testify that danger of earthquake-caused fire isn't the only reason for such steps. The fact that past earthquakes near large eastern cities haven't been of major propor-

tions should not blind us to the risk, for even a minor quake can start devastating fires which easily get out of control, especially in wintertime New England. So far as sheer violence of shaking is concerned, many types of first-class modern construction are almost automatically earthquake-proof. This is particularly true of the large buildings in a city like New York. If the public could be educated to that fact, fewer would run wildly into the streets to be hit by falling debris from the outside of buildings which are otherwise intact.

The effects of an earthquake well short of major intensity were demonstrated in Long Beach, Calif., and the vicinity on Friday, Mar. 10, 1933. Most striking was the vulnerability of certain types of school building design and construction. With demand, owing to their special uses, for many window openings and large floor spans, when these were constructed of brick and wood without bracing against horizontal forces, they failed spectacularly by the collapse of walls and fall of floors. The earthquake occurred just before 6:00 P.M. If it had come during school hours, the death toll would have been appalling. The hour of occurrence further reduced loss of life in downtown sections where the streets were nearly deserted, when parapet walls, cornices, and various ornamental units crashed into the streets.

Public interest in earthquake-proof design and construction, earthquake insurance, and public planning for emergency spurts to a high level near such areas after an earthquake. Then certain members of the community discover that proper precautions would involve condemnation of structural types in which they have an interest, others discover that an increased tax rate would result from bond issues for correcting school or public building conditions, and finally the tapering off of aftershocks and subsequent period of ground quiet removes the prod of immediate fear. Lessons, even those learned the brutal way, are soon forgotten. At the same time, other communities

look with pity on the stricken district as experiencing things remote from their own sphere, things that "can't happen here."

Seismologists are striving, and probably will have to strive for generations, to get large cities to prepare in advance rather than after the fact. Perhaps their greatest handicap is factual honesty, a scientific habit, which forces them to admit the inadequacy of their own warnings. The average responsible property owner, however, thinks nothing of insuring against fire when the statistical risk in some cities may be less than that from earthquake. We keep hoping for a miracle, for a day when a Boston or a Memphis will develop a community conscience in connection with earthquakes and earthquake fires before its number comes up; and ultimately when every large city will have building codes which require horizontal bracing in school buildings, removal of loosely hung gingerbread and precariously perched water towers, and similar obvious steps toward what, after all, is nothing but structural sanity anyway.

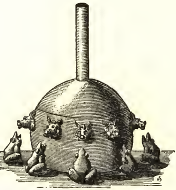
A great deal is known about the effect of foundation terrain on the violence of shaking to which a building will be subjected, and measurements can be made to determine the danger of resonance between building and ground.

The city of Berkeley, Calif., has set an excellent example in municipal planning by renewing from year to year since 1927 a "catastrophe plan" which assigns specific duties to individuals and departments. It is applicable in any city-wide emergency, whether brought about by earthquake, flood, or hurricane—for a Menace under Manhattan or a Wind over Woonsocket.

RECORDING AND INTERPRETING EARTHQUAKE VIBRATIONS

The word *seismology*, meaning the scientific study of earthquakes, and others which begin like it, such as *seismic* and *seis-*

mograph, are based on a word the Greeks had for it, *seismos*, which means "shaking like a sieve," or something to that effect. As telegraph, with "tele" for distant and "graph" for writing, means writing at a distance, so *teleseism* means a distant earthquake, *seismo*meter means something for metering or measuring shakings, and *seismo*graph means something which writes shakings.



Choko seismometer (circa A.D. 136). *A pendulum inside the sphere was supposed to indicate the direction of earth motion by knocking a ball from a dragon's mouth into a frog's.*

One of the earliest seismometers of which we have a record is credited to a Chinese named Choko. It consisted of a hollow sphere above which was a handlelike projection. Suspended from the top of the handle, with its bob in the sphere, was a pendulum. It was provided with channels which permitted it to swing in any of the eight principal directions of the compass. Protruding from the sphere at the end of each channel was a dragon's head with open mouth containing a small ball. Below each head was a frog, also with open mouth and head tipped back to catch the ball if the dragon dropped it. If ground vibrations disturbed the pendulum sufficiently, it swung into one or more of the channels and kicked the corresponding balls into

the mouths of the waiting frogs. In this way, the direction of motion in an earthquake was supposed to be indicated. As will be seen, the ground motion is actually a compound of push, shake, and a variety of mixed motions, so the design of this seismometer was based on an incorrect concept of the nature of earthquake vibrations.

The same general idea was rediscovered by a Frenchman, de Hautefeuille, in 1703. He placed a bowl of mercury in the top of a truncated hemisphere with eight channels leading from it to cups at a lower level. The direction in which the mercury slopped over into the cups during an earthquake was expected to show the direction to the earthquake's source.

Several devices were designed in the late nineteenth century with the object of stopping a clock at the instant of a shock. A modification of that idea, in 1900, was arranged to have a pendulum, when displaced by a vibration, release mercury from a funnel-shaped reservoir. The cup that received the mercury was balanced on one end of a lever. When it was weighted with mercury, it moved the lever in such a way that it lighted electric bulbs which illuminated a clock face which was then photographed to give a record of the time. The lever depressed a second arm which closed another switch and rang a gong to summon the seismologist.

The Seismograph

The main element of a modern seismograph is a weight suspended by springs in such a way that its inertia tends to keep it at rest if its support moves. There are several ways of then recording the relative motion between this mass and its support and thus obtaining a measure of the support's motion.

The principle of a seismograph's operation is demonstrated by a weight hung vertically on a spring and free to move up and

down, as in the illustration: principle of a seismograph's operation.

If *W* is displaced and then allowed to oscillate freely up and down, it will do so at a regular rate of *f* times per second, according to the weight of *W* and the stiffness of the spring; *f* is called its natural undamped frequency. If, on the other hand, *W* is at rest and the base and frame supporting it move up and down at a rate about three times *f* or faster, *W* will remain practically at rest. When this condition exists, if a lever *AB* is run from the frame through *W*, *W* becomes the fulcrum, *F*, of the simple lever system *AFB*. As *A* moves with the ground, or base, *B* at the long end of the lever moves a greater amount, according to the ratio of lever arms *BF* and *FA*. In this way, at *B* a magnified replica of the ground's motion is obtained.

A more effective method of achieving the same result is to use a light beam instead of the solid lever *AB* and to record motion of the light beam photographically. The principle, however, remains unchanged, *W* is effectively a still point in space, a phantom fulcrum.

Still another modification is to replace the solid lever *AFB* by an electrical system for measuring changes in the relative positions of *W* and the base. For instance, if a magnet attached to the base encloses with its magnetic field a coil attached to *W*, motion of the base relative to *W* causes the coil to cut magnetic lines of force and set up small currents. These currents can be fed through a galvanometer and a photographic record made of the galvanometer's response.

The same general principles can be applied to a system in which *W* hangs from springs in such a way that it moves only horizontally in one direction. A complete recording system includes two such horizontal components, operating at right angles to each other, and one vertical.

An important feature of seismographic equipment is a system for putting time marks on the records. The final objective

is to come up with records which show the many different groups of earthborne waves that reach a recording station and make it possible to measure the exact time of their arrival.

Records of great scientific value can be obtained on relatively simple equipment located in anybody's basement. On the other hand, at the Harvard University Seismograph Station in the town of Harvard, Mass., a full battery of professional equipment is housed on a hilltop in a room 22 feet square which was blasted out of solid rock and is about 15 feet below the surface of the ground. There it operates day and night, registering for posterity vibrations from the passage of railroad trains several miles away or from earthquakes on the opposite side of the globe.

Waves in the Earth

The vibrations in the earth which produce the shaking we call an earthquake are not simple things. They are in the form of waves, by which energy is transmitted through and around the earth. These waves are of several types, and our first problem is to decide upon a method for describing them.

We can start by digressing for a moment to consider the case of waves that have some features with which nearly everyone might feel he has a reasonable familiarity—waves on water. When wind ruffles the surface of a body of water, it generates waves which can be seen clearly or photographed. A light breeze makes small ones and a hurricane tremendous ones.

Dropping a pebble into a quiet pool sets up a group of ripples that travel outward over the water's surface in a pattern of concentric circles. These carry away from the pebble-water contact part of the energy which the pebble possessed as it struck. In this case, however, if at some distant point under the surface an ear or an instrument for registering sound were lis-

tening, it would detect a noise produced by the pebble striking the water. This would have been transmitted through the body of the water by sound waves, which differ greatly from the surface ripples or waves and cannot be seen by ordinary means. An extreme case of the pebble-in-water phenomenon is produced by the detonation of a depth charge.

The method of photography, when a single picture is used to describe surface waves on water, supplies us with a view of the pattern of movement over a region at a given instant of time. A series of pictures taken in rapid sequence shows how the pattern changes with time. This applies to the region as a whole, or to a given point which might be watched in successive pictures. In the latter case, a point on an originally undisturbed surface of water would be seen to move upward and forward, then downward and backward, and repeat this travel in a curved orbit each time wave after wave passed it. This method of describing the motion of an arbitrarily selected point in its path is the one commonly employed to describe each of the several types of waves which transmit energy through the earth and along its surface to produce the things we call earth, or elastic, vibrations.

As with water, there are two general classes of earthborne elastic waves: (1) *body waves,* which travel through the interior of the mass, and (2) *surface waves,* which travel only along the surface. There are two types of body waves and four types of surface waves now recognized.

1. PUSH (OR COMPRESSIONAL) WAVE. As this wave advances in the ground, it causes a particle in its path to move back and forth along the line of the wave's advance as though it were being pushed and pulled rhythmically by some hidden mechanism. The length of time that elapses between successive pushes is called the *period* of the wave, and the distance between adjacent regions of push, or compression, is the wave

length. In seismological literature, this wave is sometimes called the *long*itudinal, because particles in its path move *along* the line of travel.

Ordinary sound is a push wave, in which the zones of compression reach the human ear at a rate that permits it to "hear" them.

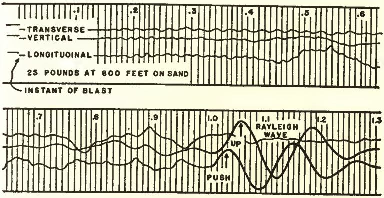
2. SHAKE (OR SHEAR) WAVE. This wave produces shearing displacements as contrasted to compressional displacements in the push wave. Compressional displacements change the volume of a material without changing its shape. Shearing displacements change the shape without changing the volume. An example of this would be a deck of cards first stacked with each card exactly in line with the one below, then arranged with each card slipped along the one below it by the same amount. In the latter arrangement, the deck would have a new shape but would still occupy the same volume in space.

One way to set up a picture of the relationship between particle movement and wave form advance in the shake wave is to imagine a rope fastened to a wall at one end and held in a man's hand at the other, some distance from the wall. If the man moves his hand up and down regularly, a wave form travels along the rope to the wall. As the wave form moves toward the wall, however, particles of the rope actually move only up and down as did the man's hand. In other words, they move at right angles to the direction of the wave form's advance. The same is true if the man's hand moves from side to side instead of up and down.

A closer analogy to conditions in the earth is obtained if you replace the rope by an imaginary rather large block of stiff jelly. If the face toward you is moved back and forth sidewise, or up and down, parallel to itself, it is given what is called a *shearing displacement*. This disturbance will advance through the jelly toward the wall, but as it does, particles in its path will swing sidewise parallel to the face that was first displaced.

A shake wave moves through solid ground by producing shearing displacements in its path. Its speed in any given earth material is usually about three-fifths of the speed of the push wave in the same material.

In seismological literature, the shake, or shear, wave is frequently called a *transverse wave* because particles in its path



Seismographic record of a Rayleigh wave generated by 25 pounds of dynamite 800 feet away.

are displaced in a direction transverse to that in which the wave form advances.

3. RAYLEIGH WAVE. If a picture of this wave could be taken, it, more than any of the other true elastic waves, would resemble a wave on water, externally. As it passes a given point, a particle in its path moves about an elliptical path in a retrograde sense. That is, at the top of its path the particle is moving toward the source from which the wave came instead of away from it as in a water wave. The length of time that elapses between the passage of successive crests is called the *period* of the wave, and the distance between adjacent crests is the wave length. Periods of 15 to 20 seconds are common, with wave lengths of 30 to 40 miles. This wave is named for John William

Strutt, Baron Rayleigh, the British scientist who first described it mathematically.

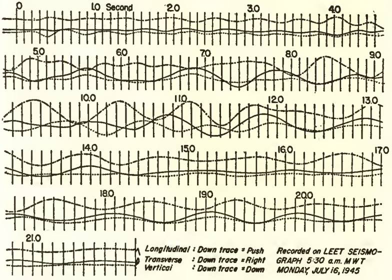
4. LOVE WAVE. This is a surface shear wave similar in general to the shake wave (No. 2, above) except that particles in its path move only on a horizontal plane at right angles to the direction of the wave's travel, and it is confined to a relatively shallow surface zone. It is named for the British mathematician, A. E. H. Love, who wrote equations describing it after it had been observed among the waves generated by earthquakes.

5. COUPLED WAVE. This is essentially a compound of push and shake motions in such a way that a particle in its path moves along one of the diagonals of a rectangular frame of reference facing in the direction of the wave's travel. It has not yet been officially christened in a manner analogous to that of the Rayleigh and Love waves because its observational discovery by Leet and first description in 1939 are so recent that a mathematical description has not been offered. Its reality was spectacularly confirmed in a record of ground motion from the atomic bomb test in New Mexico, Monday, July 16, 1945.

6. HYDRODYNAMIC WAVE. This record of ground motion resulting from detonation of the test atomic bomb in Jornada del Muerto Valley, New Mexico, was of particular value to seismology because it provided a simple vertical impact on the ground's surface with a large amount of energy. Analysis of the record revealed that the largest wave on it was not strictly an elastic wave but actually one in which our reference particle in the path moves as it would for a wave on water. For this reason it is tentatively called the hydrodynamic wave. It is possible that this wave can exist only in earth materials of a granular nature, such as the surface of Jornada del Muerto Valley and a sandy terrain in Arkansas, where the wave has also been recorded. A great deal of work will have to be done before the story of this new wave is fully known.

When a break in the earth's crust occurs, both push and

shake waves are generated simultaneously. They immediately start out in all directions from their point of origin but at different speeds. It is as though a streamlined passenger train and a fast freight started together on parallel tracks. Several miles away, one will be definitely ahead of the other. Of the earth-

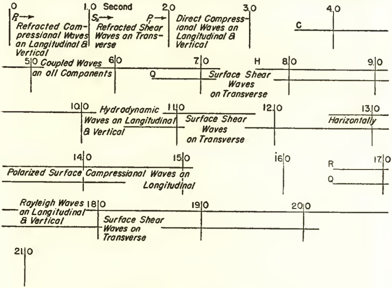


Record of earth motion set up by the first atomic bomb. A key to the wave types is given on page 78.

quake waves, the push wave is the faster. It reaches distant points first, as a result, and before its exact physical nature was understood, it was called simply the *primary wave*. By the same token, the wave coming in second was called the *secondary wave*. From these names came the symbols which are commonly used for them, *P* and *S*. The relationships are thus: push-primary-*P*; shake-secondary-*S*. During investigations prompted by the discovery of the coupled wave, it has been found at the Harvard Seismograph Station that the earlier noncommittal designation, secondary, may still be safest, be-

cause the S-waves are far from the pure shear or shake waves they were believed to be for half a century.

Last but not least are the largest and longest, the surface waves, which are thought to be generated when P and S cause

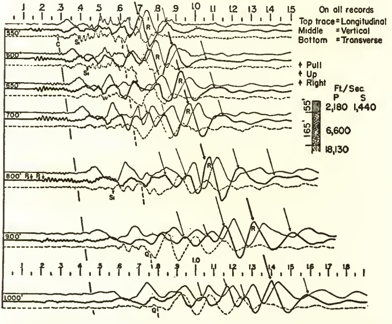


Key to wave types on page 77.

large displacements at the surface near their place of origin, and travel with the slowest speed of all, a mere 2½ miles per second. For these, originally because of their largeness, the symbol L is used. They sometimes stretch out with 100 miles or more from crest to crest. Their size depends in part upon the size of P and S near the focus, where surface waves are generated. Accordingly, they should be very small or entirely absent in the case of a deep-focus earthquake, when P and S have to travel a relatively long distance before reaching the surface to generate surface waves. They are.

In addition to traveling with different speeds, P and S differ

in another important respect. P can travel in a solid, liquid, or gas, because all these can be compressed in varying degrees. The modern method of determining ocean depths is to send a push wave (a sound wave) into the water from a boat and



Spreading pattern of wave motion between 550 feet and 1,000 feet from small dynamite shots. Push waves, P; Shake waves, S; Coupled waves, C; Love waves, Q; Rayleigh waves, R. Inset shows geological section of 55 feet of sand and 165 feet of clay resting on syenite.

measure the length of time it takes to hit the bottom and be reflected back to a detector on the same boat. In contrast to this, the shake wave can only exist in materials which resist attempts to shear, that is, distort them or change their shape. These do not include liquids and gases, molecules of which move over and around each other with the greatest of ease. The S wave, therefore, cannot exist in a liquid or a gas. This

fact has an important bearing on seismological information about the earth's central core.

The difference between speeds of *P* and *S* is a great convenience to seismologists. After the waves start simultaneously from an earthquake's focus, *P* gains progressively on *S*. A place 100 miles away is reached by *P* 20 seconds before *S* gets there; 1,000 miles away, *P* is 2 minutes and 40 seconds ahead of *S* and 4 minutes ahead of *L*; 2,000 miles away, *P* leads *S* by 4 minutes and 52 seconds, and at 7,175 miles by an even 12 minutes, with *L* at this last distance more than half an hour behind *P*.

Interpretation of Records of Earth Waves

Seismographs show when the ground is disturbed by vibrations of any of these types. They make their records with time marks on them so that the exact time of any disturbance, as well as its existence, is recorded. Accordingly, when an earthquake like that at San Francisco in 1906 has a place of origin which is fairly well known from surface evidence or distribution of its surface effects, and the distances from that to various seismograph stations that recorded the vibrations are thus known, it is possible to make timetables for the intervals between *P*, *S*, and *L* (as well as other waves) as they reached known distances.

In addition to this information, the seismograph station records would show the exact time of day at which these waves reached the different stations. So, by working backward, it is possible to figure the instant at which *P* and *S* were together, that is, the time of the earthquake at its source. When this has been done, the intervals between the waves can be supplemented by the exact length of time required for them to reach the different distances.

Such tables as these are essential tools of the seismologist. They are based entirely on experience. When the records of

a station, which are ordinarily changed daily, show an earthquake with P, S, and L clearly evident, the observer determines the intervals between them. By using the interval table, he can find at once the distance to which those intervals apply. For example, if he observes that S arrived 8 minutes after P, he concludes from the table that the earthquake was 4,000

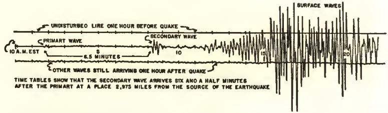
SAMPLE INTERVAL TABLE FOR *P*, *S*, AND *L*

Distance from source, miles	Time interval between *P* and *S* (*S* minus *P*)		Time interval between *P* and *L* (*L* minus *P*)	
	Min.	Sec.	Min.	Sec.
100	—	20	—	—
1,000	2	45	4	00
2,000	4	52	8	20
3,000	6	30	13	30
4,000	8	00	18	00
5,000	9	25	24	30
6,000	10	44	29	00
7,000	11	49	35	20

SAMPLE TIME TABLE FOR *P*, *S*, AND *L*

Distance from source, miles	Travel-time for *P*		Travel-time for *S*		Travel-time for *L*	
	Min.	Sec.	Min.	Sec.	Min.	Sec.
100	—	27	—	47	—	—
1,000	3	20	6	00	7	20
2,000	5	56	10	48	14	16
3,000	8	00	14	30	21	30
4,000	9	50	17	50	27	50
5,000	11	26	20	51	35	56
6,000	12	43	23	27	41	43
7,000	13	50	25	39	49	10

miles away. He then notes that *P* arrived at, say, 12 minutes and 22 seconds after 4:00 A.M. From the travel-time table, it appears that *P* requires 9 minutes and 50 seconds to travel 4,000 miles. It therefore started that length of time before it

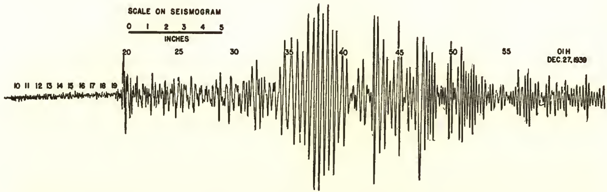


Record of an earthquake, showing primary, secondary, and surface wave groups.

reached the station in question, so the time of the earthquake at its source was 4:12:22 minus 9 minutes 50 seconds, or 4:02:32, that is, 2 minutes and 32 seconds after 4:00 A.M.

This process is carried through by all seismograph stations which record a quake. The times they compute for the instant of the earthquake should, of course, be in close agreement. Arcs drawn on a globe about each station, with radii equal to the computed distances, intersect at or near the center of the disturbance, and the earthquake is located.

The procedure for instrumentally locating earthquakes is, thus, essentially simple, though it has at times been cloaked in an aura of mystery by enthusiastic journalists, when unusual circumstances brought results into spectacular relief. On Thursday, Dec. 16, 1920, seismologists all over the world found on their records an exceptionally severe earthquake. Each station computed the distance indicated by its records. The information was transmitted to certain central bureaus, where it was assembled and used to determine the location of the earthquake by the next day. Owing to the unusual intensity, the event was announced to the press, unlike many lesser shocks



Harvard Seismograph Station's record of a large destructive earthquake near Erzincan, Turkey, Dec. 26, 1939. Primary waves began just before 10 minutes and secondary just after 19 minutes, with surface waves at about 34 minutes. S minus P interval was 9 minutes 52 seconds, which is the interval for a distance of 5,300 miles. For that distance, the travel-time of P was 11 minutes 52 seconds.

which fail to make the news because of their common occurrence. It was stated that a very severe earthquake had occurred at 5 minutes and 43 seconds after twelve o'clock, Greenwich Time, Dec. 16, 1920, in the vicinity of 35.6° N., 105.7° E. That placed it in the province of Kansu, China, which is about 1,000 miles inland west of Shanghai, on the border of Tibet. It is densely populated, but isolated. No reports of damage were received, and the matter was soon forgotten by the general public, but not by the seismologists, who dislike mysteries of that sort. Three months later it was cleared up by a survivor who staggered into the range of modern communications with a story of catastrophe on the day and at the time announced, which killed an estimated 100,000 persons and created untold havoc by causing the great landslides already described.

On Monday, May 23, 1927, Science Service announced that at 5:33 P.M. EST the previous day, there had been another severe earthquake not far from this Kansu region, and it might be months again before details were received. On Friday, July 29, the same service mailed a story about information which had just got out from the devastated area, reporting another 100,000 killed or injured (that same convenient round number) in the region defined by the seismological data published eighteen hours after the earthquake occurred.

There are some things nowadays faster than earthquake waves themselves, however, in bearing news of catastrophe. In Manila, Philippine Islands, at 6:59 P.M. on Friday, Aug. 20, 1937, a boat carrying American refugees from the Shanghai unpleasantness was about to dock. Reporters were on hand for stories, which it seemed likely were to be had. The story that broke first, however, was of an earthquake nearby which gave Manila the severest shaking it had had for some time. No serious damage was done, but the story was filed for transmission with unusual promptness. It was flashed to North America and found its way to the Boston office of a news agency. An oper-

ator there picked up a phone and called the Harvard Seismograph Station at Harvard, Mass., 8,400 miles from Manila, an hour after the earthquake happened, to inquire whether the disturbance had been recorded. The conversation took place ten minutes before the earthquake's surface waves reached that station.

On rare occasions, the records of a single station are sufficient to permit a rough estimate of the earthquake's location from them alone. With instruments recording north-south motion as well as east-west motion and vertical, if the first displacement from the push wave is large enough, its direction can sometimes be fixed within reasonable limits. The Harvard Station's seismologist found himself with just such an opportunity four months after the Manila incident. On the morning of Thursday, Dec. 23, 1937, the photographic records of that station were removed and developed shortly after nine o'clock as usual. It was found that the ground was still shaking there from the waves of a severe earthquake which had happened about an hour before. The interval between *P* and *S* was 5 minutes and 32 seconds, placing the distance just over 2,400 miles. The travel-time table shows that the push wave travels that distance in 6 minutes and 48 seconds, and the push wave reached the Harvard Station at 24 minutes and 48 seconds after 8:00 A.M. EST. Accordingly, the earthquake had occurred at 18 minutes after 8:00 A.M., 2,400 miles away. The first push had been toward the north and east, about equal amounts, indicating that it had come nearly from the southwest. That direction and distance defined a point not far from Mexico City. This information was telephoned to the reporter who had called about the Manila quake, with an off-the-record remark that his service was slipping. Half an hour later he received word direct from Mexico City that some damage had been done there, and communications with certain interior points were broken by a severe earthquake at 8:18 A.M.

As a Matter of Cores

This discussion should not be allowed to leave the impression that a seismologist's life is just one *P*, *S*, and *L* after another. As the waves from an earthquake are traced outward at successively more distant seismograph stations, it is found that something happens just beyond 7,000 miles from the earthquake's source. The first recorded wave fails to conform to the schedule established up to that point for *P*. It is late. Worst of all, *S* disappears, or gets so weak that it is lost in the shuffle. This doesn't mean that the record is a blank until surface waves arrive, for in cutting this explanation down to fit our present interests, it has been necessary to omit reference to any of several scores of combination waves which result from *P* and *S* bouncing around inside the earth, changing from one to the other and back again, and in a variety of ways complicating the issue until a distant seismograph station records the arrival of waves of some kind for hours after a large earthquake.

So when we say that *S* disappears, or is lost in the shuffle, we mean that at the time set by schedules for shorter distances, there is no longer a prominent upstanding wave of the type *S* had been up to then. Nor is there anything of the sort a short time later, as there would be if *S* were merely delayed as *P* was. *S*, as known short of 7,000 miles, just isn't there at all.

It can be shown that *P* waves which reach a surface point about 7,000 miles from an earthquake have had to penetrate close to 1,800 miles into the interior. This is not the depth penetrated by a chord of the earth-sphere, the shortest geometrical path, because the actual path is slightly curved as the waves follow the shortest-time rather than the shortest-distance path. We thus learn from the *Strange Case of the Late P and the Missing S* that the earth has a definite core, which begins 1,800 miles below the surface. Whatever its chemical constitution, it is in a condition which will not transmit a shake wave,

that is, it is either a gas or a liquid or of such low rigidity that it takes most of the shake out of *S* and some of the push out of *P*.

The point has nothing to do with earthquakes, but there is evidence of a sort which controls to some extent the guesses that might be made as to the composition of this core. The earth, the other planets, and many of the wandering chunks of matter that enter our atmosphere as meteorites are believed to have had a common origin with or by eruption from the sun. Accepting this premise, in the best tradition of Aristotle, it is no far cry to conclude that the core of the earth is dominated by a combination of nickel and iron, which is found in large numbers of meteorites. Astronomers and physicists lend weight to this view by computing the mass of the earth. They find it cannot be as light throughout as are the materials at the surface, if their answer is correct, which it probably is. A heavy core takes care of the situation.

The first push waves start away from the focus much as would ripples from a pebble dropped into a quiet pond. When they strike the core, they are bent as light waves are by a lens. One result of this is that certain distances cannot be reached either by the direct push wave or by the one which has been bent by the core and has emerged on the far side. These distances are said to be in a *shadow zone* for the direct push waves. The front of the disturbance reaches the opposite side of the globe in 20 minutes and 7 seconds.

From studies of the speeds and general behavior of push waves and shake waves at different depths in the earth, seismologists have concluded that the globe has a crystalline skin composed of at least two and possibly three or four layers under continents, with fewer under deep ocean basins. Below a depth of 300 to 400 miles, there seem to be no sharp boundaries indicating sudden changes of material until the core is reached at 1,800 miles. Geologists, judging from materials which come out of many volcanoes and from what can be ob-

served at the surface, have concluded that the outermost layer is dominantly granitic and the next one down is a denser substance intermediate in composition, while under it is a world-wide layer of basalt, the dark, heavy, fine-grained material known at the surface as "trap-rock." It is composed dominantly of oxides of silicon (50 per cent), of aluminum (15 per cent), of calcium (10 per cent), of magnesium (6 per cent), and of iron (12 per cent). From the mobility of the crust throughout geological time, it appears likely that beginning at no very great depth the materials, whatever they are, possess less strength than crystalline rocks at the surface. They are by no means weak, but will flow under stress. It is even possible that great heat in the deep interior produces convection currents in the earth body which rise from the internal furnace, push against the outer crust, spread horizontally until slightly cooled, then sink again. The motion is pictured as slow enough to require a hundred million years or more for a mass to negotiate one loop.

Night photograph of Vesuvius erupting in 1944. Lightning is caused by charges developed as bombs and dust mill around in the eruption cloud. Molten lava produced the spots of light on the mountain slopes. (Photo by United States Army)

Vesuvius erupting in 1944. The dark outline of the original mountain, which was shattered in 79, contrasts with the lighter modern cone. (Photo by United States Army)

Part of panorama of Yokohama, Japan, after earthquake and fire of Sept. 1–2, 1923.

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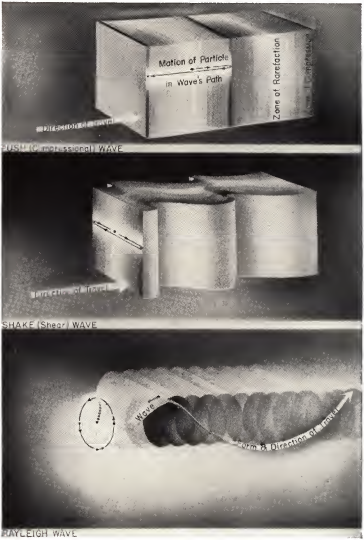
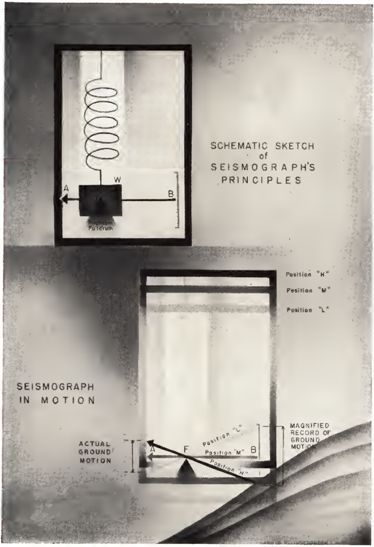
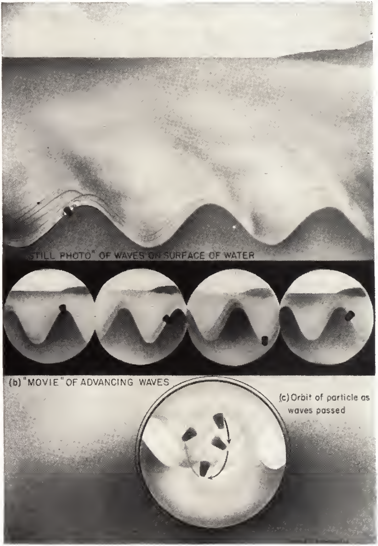


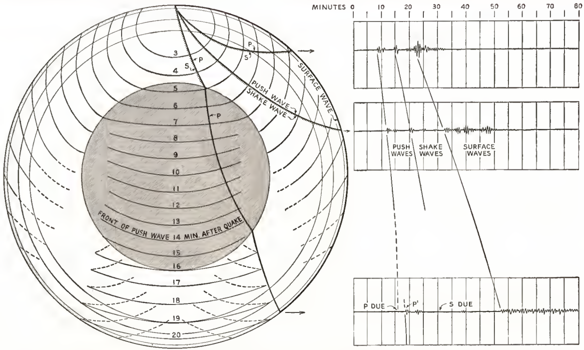
Motion produced by 3 important wave types.



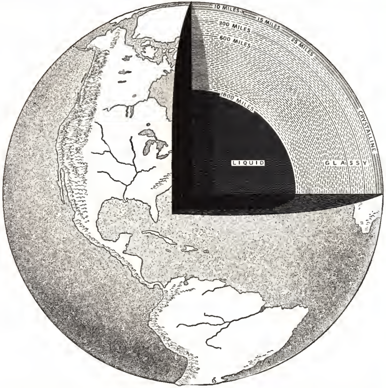
Principle of a seismograph's operation.



Methods for illustrating or describing wave motion.



Successive positions of the advancing front of push waves in the earth's interior. Also shown are the paths of P, S and surface waves to three different distances, with the seismograms for those distances. The effect of the core in delaying P and eliminating S is illustrated at the greatest distance.



Structure of the earth's interior as deduced from seismological evidence supplemented by geological reasoning.

Ruins of Pompeii, buried by an eruption of Vesuvius *which began around noon on Aug. 24, 79. (From* Aspects of the Earth, *by* N. S. *Shaler, published by Charles Scribner's Sons, 1890.)*

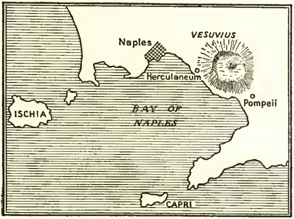
Volcanoes

Hell's fires have been brandished before the peoples of all nations by their religious leaders. A tangible variety with all the popular trimmings of brimstone was frequently observed by members of the early Mediterranean civilizations, issuing from certain of their mountains. To the Romans this phenomenon was surface evidence of activity at the forges of Vulcan as arms were prepared for Mars, so the mountains came to be known as vulcanoes, then volcanoes.

MORE CATASTROPHE

The contribution of a volcano, Mt. Pelée, to the world's catastrophes has been described. Another, perhaps even better known, was that of the eruption of Mt. Vesuvius in August of the year A.D. 79, which destroyed the cities of Herculaneum, on its southwest flank, and Pompeii, on the southeast. Nearly seventeen centuries later the buried remains of those doomed cities were discovered, and the story they told gripped the world's imagination. Roman sentries were buried at their posts. Family groups in the supposed safety of subterranean vaults were cast in molds of volcanic dust cemented to a rock-like hardness with their jewels, candelabra, and the remains of food which they had hoped would sustain them through the emergency. Suffocating clouds of dust, steam, and hot gases brought death. Subsequent falls of debris effected burial in a manner that framed the victims in a gigantic still picture cut from the movie of their final terror, surrounded by the undimmed color and form of their ancient civilization.

Vesuvius stands on the shore of the Bay of Naples on the west coast of southern Italy. The Island of Ischia, on the western border of the bay, in the fifth century B.C. was the site of the first of a number of Grecian settlements in the area. This island was the scene of many violent volcanic eruptions, but Vesuvius slept on, and to the people of the time it was just



Region around Mt. Vesuvius, near Naples, Italy.

another hill. Around Vesuvius, along the bay and on its vine-clad slopes themselves, there grew colonies of wealthy Romans seeking escape from the turmoil of Rome. In the year A.D. 63, there began a series of strong earthquakes. Then around noon on Aug. 24, 79, after a thousand years of repose, Vesuvius began to erupt.

A great naturalist of that day, Pliny the Elder, was then admiral of the Roman fleet stationed in the port of Misenum, later known as Baiae, on the western shore of the bay. From letters of his seventeen-year-old nephew, Pliny the Younger, to the historian Tacitus we have an account of the elder Pliny's investigation of the eruption and his resultant death as

well as an incidental description of the development and details of the eruption.[1]

From PLINY'S LETTERS, Book VI, 16:

Gaius Plinius sends to his friend Tacitus greeting.

You ask me to write you an account of my uncle's death, that posterity may possess an accurate version of the event in your history. . . .

He was at Misenum, and was in command of the fleet there. It was at one o'clock in the afternoon of the 24th of August [A.D. 79] that my mother called his attention to a cloud of unusual appearance and size. He had been enjoying the sun, and after a bath had just taken his lunch and was lying down to read: but he immediately called for his sandals and went out to an eminence from which this phenomenon could be observed. A cloud was rising from one of the hills which took the likeness of a stone-pine very nearly. It imitated the lofty trunk and the spreading branches . . . It changed color, sometimes looking white, and sometimes when it carried up earth or ashes, dirty and streaked. The thing seemed of importance, and worthy of nearer investigation, to the philosopher. He ordered a light boat to be got ready, and asked me to accompany him if I wished; but I answered that I would rather work over my books. In fact he had himself given me something to write.

He was going out himself, however, when he received a note from Rectina, wife of Caesius Bassus, living in a villa on the other side of the bay, who was in deadly terror about the approaching danger and begged him to rescue her, as she had no means of flight but by ships. This converted his plan of observation into a more serious purpose. He got his men-of-war under way, and embarked to help Rectina, as well as other endangered persons, who were many, for the shore was a favorite resort on account of its beauty. He steered directly for the dangerous spot whence others were flying, watching it so fearlessly as to be able to dictate a de-

[1] Excerpts from a translation by Professor J. G. Croswell for Professor N. S. Shaler of Harvard, as published by the latter in his *Aspects of the Earth* (Charles Scribner's Sons, 1896).

scription and take notes of all the movements and appearances of this catastrophe as he observed them.

Ashes began to fall on his ships, thicker and hotter as they approached land. Cinders and pumice, and also black fragments of rock cracked by heat, fell around them. The sea suddenly shoaled, and the shores were obstructed by masses from the mountain. He hesitated awhile and thought of going back again; but finally gave the word to the reluctant helmsman to go on, saying, "Fortune favors the brave. Let us find Pomponianus." Pomponianus was at Stabiae, separated by the intervening bay (the sea comes in here gradually in a long inlet with curving shores), and although the peril was not near, yet as it was in full view, and as the eruption increased, seemed to be approaching, he had packed up his things and gone aboard his ships ready for flight, which was prevented, however, by a contrary wind.

My uncle, for whom the wind was most favorable, arrived, and did his best to remove their terrors. He embraced the frightened Pomponianus and encouraged him. To keep up their spirits by a show of unconcern, he had a bath; and afterwards dined with real, or what was perhaps as heroic, with assumed cheerfulness. But meanwhile there began to break out from Vesuvius, in many spots, high and wide-shooting flames, whose brilliancy was heightened by the darkness of approaching night. My uncle reassured them by asserting that these were burning farm-houses which had caught fire after being deserted by the peasants. Then he turned in to sleep, and slept indeed the most genuine slumbers; for his breathing, which was always heavy and noisy, from the full habit of his body, was heard by all who passed his chamber. But before long the floor of the court on which his chamber opened became so covered with ashes and pumice that if he had lingered in the room he could not have got out at all. So the servants woke him, and he came out and joined Pomponianus and others who were watching. They consulted together as to what they should do next. Should they stay in the house or go out of doors? The house was tottering with frequent and heavy shocks of earthquake, and seemed to go to and fro as if moved from its foundations. But in the open air there were dangers of falling pumicestones, though, to be sure, they

were light and porous. On the whole, to go out seemed the least of two evils. With my uncle it was a comparison of arguments that decided; with the others it was a choice of terrors. So they tied pillows on their heads by way of defence against falling bodies, and sallied out.

It was dawn elsewhere; but with them it was a blacker and denser night than they had ever seen, although torches and various lights made it less dreadful. They decided to take to the shore and see if the sea would allow them to embark; but it appeared as wild and appalling as ever. My uncle lay down on a rug. He asked twice for water and drank it. Then as a flame with a forerunning sulphurous vapor drove off the others, the servants roused him up. Leaning on two slaves, he rose to his feet, but immediately fell back, as I understand, choked by the thick vapors, and this the more easily that his chest was naturally weak, narrow, and generally inflamed. When day came (I mean the third after the last he ever saw), they found his body perfect and uninjured, and covered just as he had been overtaken. He seemed by his attitude to be rather asleep than dead. . . .

From Book VI, 20:

Gaius Plinius sends to his friend Tacitus greeting.

You say that you are induced by the letter I wrote to you when you asked about my uncle's death to desire to know how I, who was left at Misenum, bore the terrors and disasters of that night. . . .

My uncle started off and I devoted myself to my literary task, for which I had remained behind. Then followed my bath, dinner, and sleep, though this was short and disturbed. There had been already for many days a tremor of the earth, less appalling, however, in that this is usual in Campania. But that night it was so strong that things seemed not merely to be shaken, but positively upset. My mother rushed into my bedroom. I was just getting up to wake her if she were asleep. We sat down in the little yard, which was between our house and the sea. I do not know whether to call it courage or foolhardiness (I was only seventeen), but I

sent for a volume of Livy and, quite at my ease, read it and even made extracts, as I had already begun to do. And now a friend of my uncle's, recently arrived from Spain, appeared who, finding us sitting there and me reading, scolded us, my mother for her patience, and me for my carelessness of danger. None the less, industriously I read my book.

It was now seven o'clock, but the light was still faint and doubtful. The surrounding buildings had been badly shaken, and though we were in an open spot, the space was so small that the danger of a catastrophe from falling walls was great and certain. Not till then did we make up our minds to go from the town. A frightened crowd went away with us, and as in all panics everybody thinks his neighbors' ideas more prudent than his own, so we were pushed and squeezed in our departure by a great mob of imitators.

When we were free of the buildings we stopped. There we saw many wonders and endured many terrors. The vehicles we had ordered to be brought out kept running backward and forward, though on level ground; and even when scotched with stones they would not keep still. Besides this, we saw the sea sucked down and, as it were, driven back by the earthquake. There can be no doubt that the shore had advanced on the sea, and many marine animals were left high and dry. On the other side was a dark and dreadful cloud, which was broken by zigzag and rapidly vibrating flashes of fire, and yawning showed long shapes of flame. These were like lightnings, only of greater extent. . . .

Pretty soon the cloud began to descend over the earth and cover the sea. It enfolded Capreae and hid also the promontory of Misenum. Then my mother began to beg and beseech me to fly as I could. I was young, she said, and she was old, and too heavy to run, and would not mind dying if she was not the cause of my death. I said, however, I would not be saved without her; I clasped her hand and forced her to go, step by step, with me. She slowly obeyed, reproaching herself bitterly for delaying me.

Ashes now fell, yet still in small amount. I looked back. A thick mist was close at our heels, which followed us, spreading out over the country, like an inundation. "Let us turn out of the road," said I, "while we can see, and not get trodden down in the darkness by

the crowds who are following, if we fall in their path." Hardly had we sat down when night was over us—not such a night as when there is no moon, and clouds cover the sky, but such darkness as one finds in close-shut rooms. One heard the screams of women, the fretting cries of babes, the shouts of men. Some called their parents, and some their children, and some their spouses, seeking to recognize them by their voices. Some lamented their own fate, others the fate of their friends. Some were praying for death, simply for fear of death. Many a man raised his hands in prayer to the gods; but more imagined that the last eternal night of creation had come and there were now no gods more. There were some who increased our real dangers by fictitious terrors. Some said that part of Misenum had sunk, and that another part was on fire. They lied; but they found believers.

Little by little it grew light again. We did not think it the light of day, but a proof that the fire was coming nearer. It was indeed fire, but it stopped afar off; and then there was darkness again, and again a rain of ashes, abundant and heavy, and again we rose and shook them off, else we had been covered and even crushed by the weight. . . . At last the murky vapor rolled away, in disappearing smoke or fog. Soon the real daylight appeared; the sun shone out, of a lurid hue, to be sure, as in an eclipse. The whole world which met our frightened eyes, was transformed. It was covered with ashes white as snow. . . .

Edward Bulwer-Lytton (Lord Lytton), in 1834, reanimated the scene briefly in his romantic novel *Last Days of Pompeii.* The final events include a description of the eruption based upon the accounts of the younger Pliny.

The year 1783 brought volcanic catastrophe to Iceland. In May, about 30 miles southwest off the coast at Cape Reykianas, a submarine eruption produced a new island at 63°25′ N., 23°44′ W. It was christened Nyoe, or New Island, and claimed for Denmark, but within a year natural processes had reduced it to a shoal under 5 to 30 fathoms of water. Then on Wednesday, June 11, 1783, after a series of violent earthquakes near

Mt. Skaptar, 80 miles east of Mt. Hecla and about 200 miles from New Island, immense outpourings of lava began from twenty-two vents along a 10-mile line, the so-called Laki fissure. They poured a great flood of lava into the channel of the Skapta River, drying up the river and overflowing the channel which was in places 400 to 600 feet deep and 200 feet wide. The resultant damming of tributaries of the Skapta flooded many villages. The lava flood, followed by another a week later and a third on Sunday, Aug. 3, filled a former lake, an abyss at the foot of a waterfall, and spread out into great tongues 12 to 15 miles wide and 100 feet deep. Melting snow and diverted drainage forced floods of water into the bed of the River Hverfisfliot and wrought further havoc. Activity around Mt. Skaptar continued for two years. In April, 1784, it was supplemented by other eruptions in snow-covered peaks near Mt. Skeidhard, which caused floods of water, ice, sand, and volcanic dust to devastate the land even further. Directly, and through hunger and disease, these events brought death to over 9,000 persons (nearly a fifth of the population of Iceland at that time) and 230,000 head of cattle.

A hundred years later, one of the greatest explosions of modern times occurred at Krakatoa in 1883. Krakatoa was a volcanic island in Sunda Strait, which separates Java from Sumatra. It is a vent near the intersection of a structural crack crossing the one along which are located the active peaks of Java. On the afternoon of Sunday, Aug. 26, 1883, it started a series of explosions which culminated the next day at 10:20 A.M. with a gigantic spasm that blew two craters to bits and and left water 900 feet deep in one place where the island had been 2,600 feet high. The noise was heard in Australia and a wave of pressure in the air was recorded by barographs around the world. A wave of water set up by the event drowned 36,500 persons in the low coastal villages of western Java and southern Sumatra. Columns of ash and pumice went miles into the air.

By the next year, pyrheliometric observations, which give the amount of the sun's heat reaching the earth's surface, showed it to be only 87 per cent normal. A similar effect of about the same magnitude was observed following a series of eruptions in 1902.

SOME GENERAL FEATURES OF VOLCANOES

Volcanoes are in many ways more interesting and instructive than earthquakes. From a human standpoint, they can be located definitely as danger spots, and they rattle before they strike. Catastrophe such as that which overwhelmed St. Pierre, Herculaneum, Pompeii, and Iceland can be averted more and more successfully as scientific knowledge of the subject expands. Also, volcanic vents pour out materials from greater depths than can be observed by any other means and supply evidence bearing upon the constitution and history of the earth as a planet.

Shape

A volcano is a special kind of mountain. It differs structurally and genetically from the majority of the world's mountains. Externally, it is characterized by a symmetry of shape. Mt. Ararat, of Biblical fame as the alleged landing place of Noah's ark, is a 17,000-foot sample of a volcanic cone. Mt. Popocatepetl in Mexico, Mt. Fuji in Japan, and Mt. Mayon in the Philippines are examples of unusually perfect development of the shape toward which most volcanoes tend. In addition to this, the area in the vicinity of a modern volcano is marked by the presence of volcanic ash and lava quite different from the rocks of which most mountains are composed.

As far back as records in the rock take us into the earth's history, volcanoes are found to have been present. The ancient,

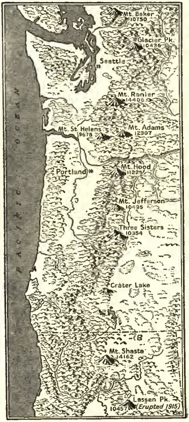
truly dead ones have been worn away where they had their necks stuck out, and we can today view remnants of their throats and the pools of once-molten rock upon which they drew for supplies. A fossil volcanic neck, with some of its feeding dikes, protrudes from the surface today near Farmington, N. M., where it is called Shiprock. Several of the White Mountains of New England are blocks of rock which foundered in a molten pool that supplied 10,000 feet of lava beds and volcanic debris to an ancient land surface through volcanic vents some 200 or 300 million years ago.

Distribution

Modern volcanoes, with the exception of some special deep-sea islands, are related to geologically young mountains festooned on the globe today. The borders of the Pacific Ocean are dotted with them. Notably active groups occur in the Aleutian Islands of the North Pacific Ocean, along the Kamchatka Peninsula and Kurile Islands, throughout the main islands of Japan and chains of islands branching from them, the Philippines, the Netherlands East Indies, and the South Pacific group of islands. The Hawaiian Islands in mid-Pacific are volcanic. The west coast of South America has its share, and Central America is particularly active. The west coast of North America is relatively inactive at the present moment, though Mt. Lassen in California erupted in 1915. At the same time, such famed peaks as Baker, Glacier Peak, Rainier, and St. Helens of the state of Washington, Hood and Crater Lake (Mount Mazama) in Oregon, and Shasta in California, lined up nearly along the meridian 122° W., are volcanoes with historic records or geological evidence of their youth.

There are records of a fairly active eruption of Mt. Baker in the 1850's. Fume was found rising from a crater in the snow by a mountain-climbing party in 1903. Mt. Rainier's crater has

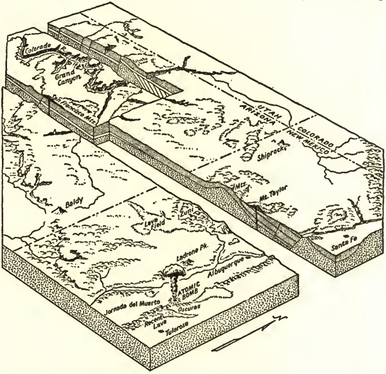
been described as from a quarter to a half mile in diameter, with bare cliffs 30 to 40 feet high bounding it and jets of steam issuing from many small vents in the rock. It is reported to have



Modern volcanoes along the meridian 122° W. in the United States.

been active about 1842, with Mt. St. Helens. Glacier Peak is a volcano 10,400 feet high, but has not been described as steaming in this century. Steam has been seen coming from the flanks of Mt. Hood by modern mountain climbers. There are

records of eruptions in 1859 and 1865. Mt. Adams has probably been active within the past century or so. Mt. St. Helens is reported to have been in activity in 1841–42. A boiling



Volcanic and structural features in the vicinity of the atomic bomb test area and the Grand Canyon of the Colorado. (In part after A. K. Lobeck)

spring feeding a cataract down the side of Mt. Shasta was observed in 1923.

At the edge of the area where the famous atomic bomb test of Monday, July 16, 1945, was conducted, near Carrizozo, N. M., is a lava flow so recent that it looks as though it should be hot to touch.

In contrast to the major cones listed above, there are sometimes areas given to a different volcanic habit. Eruptions, instead of occurring repeatedly at or near a single vent over a long period of time, will break out promiscuously from randomly distributed vents, each of which comes into being, grows from 1,000 to 3,000 feet high during a single burst of activity spread over a few months or years, and then lapses into permanent quiet. There are over 200 such vents in the vicinity of San Francisco Mountain, Arizona. The most famous eruption of this type in recent years was that of Paricutín in Mexico on Friday, Feb. 20, 1943.

Offshoots of the Pacific groups of volcanoes are to be found on the west in Java and Sumatra and on the east in islands of the West Indies. Iceland has many active vents and those of the Mediterranean basin are among the best known in the world. Regions of modern or geologically recent volcanism also include the Azores, Canary Islands, Cape Verde Islands, St. Helena Island, Ascension Island in the Atlantic, and Madagascar, Réunion, Mauritius, Rodriguez, and Kerguelen, in the Indian Ocean.

Motivation

A universal feature of volcanoes is that they are motivated by molten rock which has invaded the outer crust as what is called *magma.* Sometimes this merely supplies the heat that produces a steam or gas explosion; on other occasions, it wells out at the surface, where it is called *lava.*

Messengers like this from the interior would appear at first glance to be telling a story of some subterranean sea of molten rock. Historically, that was the first explanation offered by modern science, was fashionable for a century, and was accepted as recently as the beginning of the twentieth century. Then the registration of earthquake waves became a routine

matter, and it was found that these other messengers from the same interior denied the allegation of liquidity, at least as regards 1,800 miles of mantle over the core. Shake waves could not travel through a lake of molten rock, but they travel with the greatest of ease through whatever is there. A mechanism requiring that blobs of the core, for no particular reason, detach themselves and traverse 1,800 miles of solid stuff to cause a volcanic eruption is contrary to many laws of matter which we think we know today, and the material that comes out is vastly different from that which other evidence indicates is probably in the core. Accordingly, it has seemed desirable, even necessary, to speculate on alternative possibilities.

A useful method of speculation on this topic is to visualize a model of the earth along proposed lines and subject it to the tests of old and new observed facts. We shall, perforce, describe the 1947 model. It is known to be vastly superior to any which preceded it. It is, at the same time, certain to be modified in the future and should be examined with that fact in mind.

Lavas of the world are remarkably similar in general nature. They are, save for rare and explainable exceptions, dominantly basalt or closely related rock types. This widespread uniformity of the material that rises from depth argues for the globe-encircling shell of basalt already mentioned, to serve as the primary source for intruded and erupted molten rock. The top of this layer is now believed to be at a depth of nearly 20 miles. Down there, the basalt is pictured as quite hot, but the pressure of miles of overlying crust keeps it from melting. The same principle is illustrated when it is found that water will boil on a mountaintop at a temperature of, say, 185° Fahrenheit, but near sea level it can be heated to 200 or 210° without boiling because the atmospheric pressure on it is greater. We say that increased pressure raises the boiling point of water. In like manner, rock hot enough to melt under the pressure of one atmos-

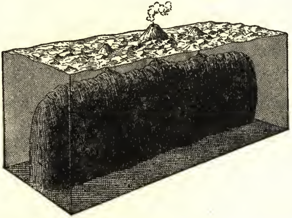
phere at the surface of the earth may not be hot enough to melt under a pressure several thousand times as great at a depth of several miles, because increased pressure raises the melting point.

In the processes of mountain making (see page 132), large segments of the outer crust are subjected to shoving, pulling, and distortion, which result in the formation of giant abyssal cracks—not open affairs, but planes of weakness where the natural coherence of the material has been overcome. Buckling of the overlying crust locally reduces the downward pressure on part of the substratum of basalt. The basalt, hot enough to melt at the reduced pressure, is forced into an abyssal crack and starts toward the surface. As it rises, the pressure on it is further reduced. This allows the formation of bubbles of gas which had been dissolved in it under pressure, like those which form in a ginger-ale bottle when the cap is removed and the bottling pressure eased. These gas bubbles course through the melt, increasing its fluidity and rapidly transferring heat upward to help the mass eat its way through the crust. Once started, the rise of the magma is a self-motivating operation as long as the heat lasts, which may be millions of years.

Thus, a large body of magma may approach the surface. Tongues and offshoots precede it, invading the rocks of the surface as what are called *dikes*, if they are wall-like masses steeply inclined, or *sills*, when they find easier access by following horizontal bedding planes. Many of these tongues reach the surface and through them large volumes of basalt pour out to chill rapidly and freeze in place. When the mode of exit is by a tubelike neck which opens its way through to outer space from some deep-seated feeder, a volcano is built up by successive gushes of material gathered about the vent in the familiar conical shape. A fossil volcanic neck has been exposed by erosion in the Grand Canyon of the Colorado River.

The major mass of magma is called a *batholith*, the "batho"

pertaining to depths and "lith" to rock, meaning "rock of the depths." There is at least one place where a batholith is believed to have got near enough to the surface to cause its roof to founder. That is in Yellowstone National Park in the United States, where heat near the surface is still sufficient to turn



A batholith with two extinct volcanoes and an active one that it is feeding.

ground water into the steam actuating geysers. In other places, batholiths have reached equilibrium by losing their upward-eating power and gradually frozen in place. The process of cooling was not simple. The primary basalt was a mixture of many materials, each of which solidified at a different temperature. Also, given sufficient time in a liquid condition, some of the heavier molecules may have tended to settle. At the same time, this melt digests some of the rocks through which it cuts to or toward the surface. A combination of these and other processes sorted the original mass until a lighter section solidified as granite. In the roots of every mountain chain of the world, old or new, are found granite batholiths, while shot through neighboring rocks are myriads of basalt dikes and sills.

Throughout geological time there have been several periods of intensive mountain making. The older ranges have had their original covers stripped off by erosion, leaving exposed the one-time roots. The White Mountains of New England are tough lava flows which resist weathering more than the surrounding granite into which they foundered when New England was younger. In Scotland and Ireland are to be found today exposed systems of basaltic dikes running in a general southwest-southeast direction, with the remnants of many volcanoes which they fed.

The alignment of groups of modern active volcanoes, as well as Pacific islands perched on volcanoes, is attributed to their relationship to abyssal cracks through which basalt welled up from the substratum.

Cycles of Activity

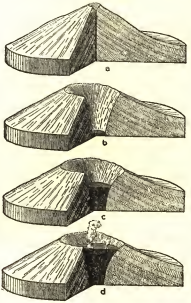
The activity of a volcano runs in cycles. A burst of violence is followed by exhaustion and quiescence, while energy is stored for another outburst. When eruption ceases, lava in the volcano's throat sometimes congeals to form a plug. This happened in Mt. Pelée and contributed to the unique character of its eruptions of 1902. Forces trapped by its plug finally accumulated until, blocked at the usual outlet, they shot an emulsionlike mixture of gas and dust out the side of the cone. This strange mixture formed a cloud which was heavier than air and shot down the mountainside to engulf the town of St. Pierre and shipping in the harbor. Greatest destruction was caused by the heat of the mass, which has been estimated at 1500° Fahrenheit.

Vesuvius supplies an example of a cycle of activity. A cycle is concluded by an explosive eruption. This leaves a large, deep crater, which proceeds to enlarge its rim and fill its interior by avalanches. Before long, liquid lava enters the bottom of the

crater and starts building it up. This continues to the accompaniment of some explosive activity until the crater is filled and the only trace of its former outline is a rim around the outside. The temperature of the internal lava increases, pent-up forces seek release by shoving small lava streams through the side of the mountain. Then comes the big blowoff, openings at lower levels help drain off the lava, repeated inrushes of lava and gas with explosive force scour the crater for a few hours or days before the violent energy subsides and the whole process begins again. The "eruption" of this volcano, as generally pictured, is thus actually only the final episode in a continuing, repeating process of building up, swelling under confined forces, explosion, and collapse.

A paroxysmal eruption of Vesuvius in 1906 was followed by seven years of repose. In 1913, the conduit opened and the normal type of external activity began. The crater steadily filled from a succession of central conelets, with minor crescendos of explosive and effusive activity at intervals. On Monday, June 3, 1929, a spectacular event in this series began with tremendous explosions and the hurling into the air of masses of incandescent material. The central conelet split and collapsed. As it fell back into the crater, lava welled out and occupied the northeastern quadrant of the crater. On the morning of June 4 the interior of the crater became a lake of effervescing lava some 500 yards in diameter. The lava overflowed into the Valle dell' Inferno and escaped down the outer slopes into the Valley of Cuppaccio toward the town of Terzigno, following the course of a lava stream in 1834. After a short interval of quiescence, from 2:30 to 7:30 P.M., there was a sudden paroxysm of activity for three-quarters of an hour. Incandescent matter rose 1,500 feet above the crater and fell in glowing showers on the slopes of the volcano. Afterwards there were loud and frequent explosions, followed by an ash cloud that rose to still greater heights. From 11:00 P.M. on June 5 to 3:00 A.M.

on June 6, there were further tremors and explosions, and columns of lava were thrown into the air to break into incandescent bombs. The lava stream extended 5 miles down the southeastern slopes, with a frontage of 900 yards. It halted 400 yards



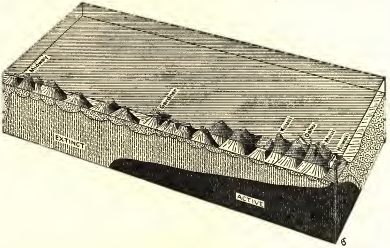
Cycle of activity at Vesuvius. (a) *Before the eruption of 1906;* (b) *after the eruption of 1906;* (c) *returning lava as it stood about June, 1913;* (d) *about April, 1926, at a stage in which lava sometimes breaks through and runs down the slopes.* (*After B. G. Escher*)

from the houses of Terzigno. The volume of lava was estimated as about half that emitted during the 1906 eruption.

With this picture of the events called an eruption, some idea can be gained of the futility of a proposal in Britain in December, 1940, that Vesuvius be bombed to start an eruption. Aside from the physical impossibility of firing that gun by pulling the trigger if it isn't loaded, the relatively slow motion by which final steps in an eruption are achieved makes it

a feeble weapon for sudden deadly assault on a countryside, as was demonstrated when an eruption finally occurred in March, 1944, after United States troops had occupied Naples.

Etna volcano, occupying an oval tract 30 miles long by 23 miles wide on the northeastern coast of Sicily, climaxed a re-



The Hawaiian Islands perched on a series of volcanoes and lava piles stretched out for 1,500 miles along a major abyssal crack in the Pacific Ocean.

cent cycle of this sort by a quieter but destructive outpouring of lava. It is 10,758 feet high, with densely populated slopes. On Thursday, Nov. 1, 1928, four streams of lava issued from the east flank at an elevation of 3,000 feet and started down the slope slowly but inexorably. Mild earthquakes preceded the eruption, distant explosions and loud subterranean rumblings accompanied it. By Wednesday, Nov. 7, the 7,000 inhabitants of Mascali at the foot of the volcano had been evacuated and lava buried the site, advancing with a front 2 miles wide and 16 feet high.

Another type of cyclical behavior was shown when, the day

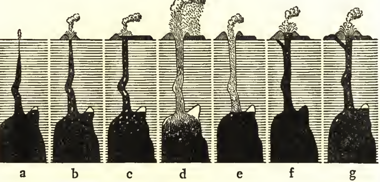
before St. Pierre was destroyed, Soufrière volcano on the island of St. Vincent, 100 miles south of Martinique, exploded violently at 1:30 P.M. In October of the same year, Santa Maria volcano, its towering height of 12,361 feet (nearly exactly equal to that of Mt. Fuji in Japan) dominating the rich coffee lands of western Guatemala, erupted with disastrous ash falls and floods. The close spacing in time of these eruptions was regarded as more than coincidence, though Santa Maria is over 2,000 miles from Pelée and Soufrière. On Sept. 16, 1929, ash eruptions began again from the crater of Mt. Pelée. Activity continued through October, and complete evacuation of St. Pierre and adjoining towns was ordered. St. Pierre by then had more than 100 houses, a club, a restaurant, shops, a market, a customhouse, and 1,000 inhabitants. A repetition of 1902 did not occur, but on Nov. 4, 1929, after three days of increased rumbling, hot ash was vomited from Santa Maria in Guatemala in an eruption which lasted three days and destroyed villages, coffee plantations, and farms.

HAWAIIAN ISLANDS

In contrast to the violence of Mediterranean volcanic eruptions of the Vesuvius and Etna types, the Hawaiian Islands supply examples of the opposite extreme, where eruptions are climaxed, with an occasional exception, by quiet flows of lava.

The Hawaiian Islands are the protruding peaks of volcanic mountains. The related islands are strung on a line 1,500 miles long trending north of west nearly parallel to the trends of the Marquesas, Society, Paumotu, Tubuai, Samoan, and other volcanic islands of the Pacific, each group presumably fed by a great abyssal crack in the earth's crust. At the northwest end are the low Ocean and Midway islands. At the southeast end is Hawaii, the highest deep-sea island in the world, with Mauna Loa towering nearly 6 miles above the ocean floor near by, and

still growing. The vent Mokuaweoweo on Mauna Loa is 9,000 feet higher than Halemaumau at Kilauea 20 miles away, yet the lava columns in each must not be directly connected to the same source chamber, for they behave independently of each



Cyclic activity of the volcano Paricutín, in Mexico. (a) *Birth of the volcano;* (b) *gas activity and ejection of debris to form crater;* (c) *breaching of cone and flow of lava;* (d) *maximum gas activity from central crater carries out top of lava column;* (e) *mild gas activity, low lava column;* (f) *lava rises in vent;* (g) *breaching of cone and renewed flow of lava.* (*After Donald E. White*)

other instead of the higher one draining out at the low one as would happen if they were connected.

In 1911, the Hawaiian Volcano Observatory began continuous scientific observations on the island of Hawaii and made the area one of the most important volcanic laboratories in the world. As so often happens, financial support for this venture has not always been commensurate with the service it renders the islands, and all science. The world has long been prone to regard billions for armaments and spectacular social experiments as more exciting than hundreds for "sitting on the lid of a volcano waiting for something to happen."

Records carry the story of Hawaii far back of the founding of

the observatory. Flows and explosions in 1790 were exceptionally violent. Preserved in the ash have been found footprints and fossil raindrops. The dust from an explosion is hurled upward in the midst of clouds of steam. It is characteristic of such times that the atmospheric moisture condenses as heavy rainfall, usually with thunder and lightning. When the dust is caught in the raindrops, the rain falls as mud. If such mud drops fall along with dry ash, or into beds of dry ash, they will form a layer of small pea-shaped pellets. Such pellets were common at the eruption of Vesuvius in 1906. The dust, roasted by the combined fire and steam activities of eruption, became a weak cement which hardened in a form that resisted erosion for long intervals.

The story told by some of the footprints accounts for their presence so near the danger of a major eruption by attributing them to soldiers of Keoua. He, considering himself the legitimate heir to the throne of the island of Hawaii, marched from Hilo with all his forces to attack the warriors of Kamehameha in Kau and Kona. He crossed Kilauea volcano, and legend has it that an eruption that night killed him and the warriors of two small villages, about eighty men in all, with their families and livestock, except for one hog. Keoua had broken the tabu of Kilauea and the goddess Pele punished him accordingly.

Episodes in the history of Hawaiian eruptions have been divided roughly into 11-year cycles, with a supercycle of about 132 years. It is probably more than coincidence that sunspots vary in a similar manner. Nobody has explained just why there should be a connection, but the earth, offspring from a parent sun, or the earth, stunted sister of a sun-and-planet brood, seems in some way to have inherited this tendency toward 11-year cycles of internal condition.

An "eruption" is a difficult thing to define. Volcanologists in observatories at Kilauea and Vesuvius have concluded that the most distinctive feature of a volcanic cycle is the short

period of repose at its end. This is often preceded by explosion, which constitutes the phase popularly known as an "eruption." At volcanoes like Kilauea and Vesuvius the lava column is visible most of the time and serves as a gauge of activity. Repose is followed by increasing internal pressure which may or may not manifest itself by the appearance of lava and building up of the cone as at Vesuvius. The volcano literally swells like a toad. At Hawaii, instruments record the tilting of the ground that results from this swelling. As the climax of pressure approaches, lava may break through the flanks or overflow the top. This is followed by collapse. At this stage some volcanoes explode violently. Others simply send out lava floods. Kilauea usually does the latter, but in 1924 it closed a 132-year supercycle with a spectacular steam-blast eruption that tossed 8-ton boulders nearly a mile from the vent and released tremendous cauliflower clouds of smoke. Steam blasts are believed to differ from normal eruptions in that the rising gas and lava from depth superheat surface ground waters, and sometimes this occurs so rapidly that the resultant pressures can be relieved only by explosion.

It is the period of high pressure in Hawaiian cycles that correlates with sunspots, according to the Volcano Observatory.

The sunspot maximum exhibited a very long interval between 1787 and 1804, and this was a turning point from high numbers to low numbers of sunspots for the maximum years. It was also the turning point at Kilauea for the supercycle that ended with the explosive eruption of 1790.

Thus volcanoes join the extensive list of terrestrial events which have been accused of relationship to sunspots or of habits showing a similar cycle: weather, magnetism, radio reception, tree growth, richness of pelts on fur-bearing animals, lake levels in Africa. A recent addition to this list was the price of stocks on Wall Street, on the theory that sunspots control

the amount of ultraviolet radiation from the sun, which affects animals, including human beings, by causing cyclical periods of physical depression, hence financial pessimism, etc.

ANALYSIS OF HIGH-PRESSURE HAWAIIAN LAVA

Period	Eruptions	Sunspot Maxima
1788–93	Probable Kilauea floods preceding 1790 explosions, and 2 flows reported in Puna	1787
1804–14	Unknown, but Hualalai floods 1800–01	1804
1814–25	Kilauea lava flood 1823, Mauna Loa unknown	1816
1836–47	Kilauea flood 1840, Mauna Loa flood 1843	1837
1851–55	Mauna Loa maximum, Kilauea maximum	1848
1859–68	3 flows Mauna Loa, Kilauea rising, overflowing	1859
1869–77	Kilauea rising, continuous summit eruption Mauna Loa	1870
1881–87	Kilauea and Mauna Loa big floods	1884
1892–99	3 flows Mauna Loa, Kilauea 1894 maximum	1893
1903–07	Flows Mauna Loa and Kilauea rising	1905
1917–20	Kilauea and Mauna Loa flooding (followed by collapse and steam-blast eruption of 1924)	1918
1926	Hoopuloa destroyed by Mauna Loa	
1929	Kilauea eruptions and earthquake crisis at Hualalai	1928

Scientists at the Hawaiian Volcano Observatory have concluded that the internal pressure under a volcanic island may be thought of as accumulating at a nearly steady rate through the ages. The volcanic vents are safety valves, and the entire island, by its weight, acts as the spring control of the valve, opening only when the pressure inside has passed a certain

amount. At Hawaii, the island safety valve has three openings, Mauna Loa, Kilauea, and Hualalai, with a heavy shell weighing down on cracked blocks below, confining forces there striving for release. Once in about eleven years the underground lava gradually and irresistibly forces itself up into cracks under the several openings and extends out along rift belts that break up the mountains into blocks. How this hot matter grades down into original source masses is not known. There may be subordinate pasty masses under each volcano fed by old cracks extending down into bigger and deeper masses representing ancestral volcanic domes. The height and size of the magma chambers inside the island and their supply of gas from the larger and deeper magma masses are what determine whether Mauna Loa, the high, or Kilauea, the low, mountain erupts. The lava is not to be pictured as a rising liquid so much as a local body of rock pudding full of frothing gas. As the gas accumulates, pressure increases, the mountain swells, and finally the safety valve lets go. The process then begins again. The volcano is literally a monster breathing fire with a slow, majestic rhythm. The island is a giant calliope playing alternately high and low notes.

The volcano Paricutín, born in Mexico on Saturday, Feb. 20, 1943, and studied in greater detail than any other newborn vent in history, has a cyclic behavior the mechanism of which may be that of a small-scale model for demonstrating some general principles. Paricutín is small scale in every respect except the publicity in the modern mode which made it one of the best advertised volcanoes of our day.[1]

A complete cycle appears to involve four stages: (1) flowing lava; (2) maximum gas activity from the central crater, without lava flow; (3) rise of lava in the vent; (4) breaching of the cone in preparation for renewal of flow.

[1] See *Paricutin's Cyclic Activity*, by Donald E. White, *Amer. Geophys. Union trans.*, 1944, Part IV, p. 621, March, 1945.

Many stories of the volcano's first hours have been told. According to the one now generally regarded as the most reliable, the first event was the rising of a thin wisp of smoke from the ground. In the course of three or four hours a hole was formed

Tongue of lava about to engulf Hoopuloa, Hawaii, Apr. 18, 1926.

30 feet deep and 10 feet in diameter, from which poured clouds of ash. The first explosion apparently did not occur until about seven hours after the first smoke appeared. The cinder cone formed by ejected material had grown to about 500 feet in height within a week and over 1,000 feet within ten weeks. The first lava flowed from a fissure about 1,000 feet north of the center of the cone two days after the eruption began and advanced more than a mile in seven weeks. The first lava flowed from the crater itself fifteen weeks after the first explosion.

Following flows of lava, pressure is temporarily relieved to some extent and gas activity increases, just as bubbling takes

place when bottling pressure is eased by removal of the cap from a bottle of soda. Explosive "blowing" results. This involves the rush of a gas-charged column so violent that it carries out the overlying lava rather than bubbling up through it. With many of its volatiles removed by this process, the remaining lava wells back into the pipe and works upward until it again emerges in flows, and the whole thing starts over again.

EFFECTS OF LAVA FLOWS ON HUMAN SETTLEMENTS

Around Vesuvius, the Hawaiian peaks, and other volcanoes, lava flows determine the form of the shore line. Between two flows will be a neat indentation to serve as a harbor and a tempting lowland attractive to farmers and fishermen as the site for homes. There they settle in a perfect trap, for it is the inevitable path of a subsequent flow. This was demonstrated on the western shore of Hawaii at the village of Hoopuloa, Sunday, Apr. 18, 1926. From a rift in the side of Mauna Loa, at a height of about 7,600 feet above sea level, lava welled out of a dozen cones each 50 to 75 feet high along a line 2 miles in length. As the flow approached the shore, it trailed naturally into the valley between two older flows. With tongues pushing forward now here, now there, by the technique of a caterpillar tractor, the advancing fronts 20 to 40 feet high roll an upper layer of boulders and gravel forward on a viscous red-hot paste inside. The hot paste overrides the track of boulders thus laid for it. Along a front 1,100 feet wide, the flow advanced upon the village of Hoopuloa at the rate of 3 feet per minute, entered it at 4:00 A.M. Apr. 18, 1926, and obliterated it.

In 1931, experts at the Hawaiian Volcano Observatory pointed out that the city of Hilo on the island of Hawaii is definitely marked for future lava flows. They stated: "It is practically inevitable that Hilo will look up some evening and see

what resembles a bright star on the northeast rift line of Mauna Loa, and a flow will start following the hollows among the flows of 1852, 1855, and 1881 in the direction of the valley of the Wailuku River. After it has been going a month, we shall know whether it is likely to keep going for a year." If so, they pointed out, red-hot tongues would course downward through tunnels and spread for months. These would invade and dry up the Hilo water supply. The main source of supply would feed through a trunk tunnel up around the 9,000-foot level and by the time the advancing front approached Hilo, it might be weakened sufficiently to permit an attempt to save the city by dynamiting the lava tunnel near its source. If, by that process, a dam could be formed to divert the stream, the source of supply would be removed from the Hilo tongue, and the city might be saved even though the flow continued. This technique is possible only in the dying stages of a flow of long duration. It would not have saved Hoopuloa. Four years later, events transpiring with greater rapidity than expected but otherwise according to prediction led to an attempt to apply the method.

The average interval between small eruptions on Hawaii following 1924 was 1¼ years, and an outbreak occurred in 1933 at the summit crater of Mauna Loa. In view of those facts and the evidence for an 11-year cycle, an eruption in 1935 on the north flank of the mountain was expected. It began on Thursday, Nov. 21. Advancing down the steepest slopes at the previously unheard-of rate of 25 miles per hour, the flow narrowly missed entering a stream bed and following it down to engulf Hilo practically without warning. As it was, the danger to Hilo seemed great enough to warrant trying to divert the flow, and army bombers were dispatched to undertake it on Nov. 27. Their objective was the lava feeder in a tunnel possibly 100 yards wide. From an altitude of 4,000 feet necessary to avoid complications from the concussion of exploding TNT bombs, the bombers had their work cut out for them to hit such a tar-

get. They failed to breach the walls confining the lava stream, though at least one bomb scored a direct hit. Twenty-four hours later the lava was photographed coursing merrily along downstream below the point of the bombing, but within three days the tongue threatening Hilo came to a halt.

Our scientist frankly admitted that the situation reminded him of an incident at the time of a flow in 1881. As it approached nearer and nearer to Hilo, the residents called for help from the princess of a neighboring island. She went at once, pronounced certain mystical formulas, then cut off some of her hair, which was thrown into the advancing lava. The flow stopped right in the outskirts of the town. In 1935, TNT was substituted for the hair, but there are suspicions that it had as much to do with stopping the flow, though the idea is still a good one.

Scientists of the Hawaiian Volcano Observatory persisted, and in December, 1936, a conference of executives, engineers, seismologists, and volcanologists of Hawaii National Park, University of Hawaii, the U.S. Geological Survey, and the Hawaiian Volcano Research Association met to set up a schedule of expected eruption dates and draw plans for the protection of Hilo harbor. Protection from lava flows had become as practical as the elimination of malaria, yellow fever, and plague from such a region—and even more important, for Hilo harbor is practically the only sheltered embayment available to shipping on the plantation side of the island of Hawaii. If it were left exposed to filling by lava, all other public works in the area would have gone for naught.

Specific proposals were made for the diversion into neighboring valleys of flows threatening Hilo harbor. By 1940, variants of an effective plan were subjected to cost estimates ranging from \$400,000 to \$2,613,800, or an average of a little over a million and a quarter dollars, requiring thirty-two months to complete, for a diversion channel and barrier about 8 miles

long to protect Wailuku River, Hilo harbor, Hilo city, sugar and wallboard factories, railway terminus and airport, representing $50,500,000 values subject to destruction.

A reviewing Board of Engineers for Rivers and Harbors, in September, 1940, reported adversely on all improvements to Hilo harbor: "The board is of the opinion that the construction of the lava barrier, while affording the desired protection to Hilo City, is not a function" proper to War Department activities at that time.

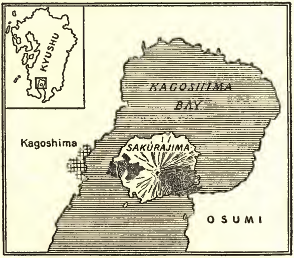
The 1935 flow, as has been mentioned, followed the 1924 by the 11-year interval normal to the Mauna Loa-Kilauea system. Between such outbreaks, there are minor events which tend also to follow a cyclical pattern. Arguing from a striking parallelism between events of 1843–59 and those of 1935 onward, with duplicated events in 1940 (cf. 1849–51) and 1942 (cf. 1852), Dr. T. A. Jaggar pointed out that "the 1855 and 1859 eruptions of Mauna Loa were the most voluminous of the nineteenth century. Therefore if it is a recurrent analogy by structure, location and breakage, by cyclical interval, and by requirements of periodic subterranean accumulation, the probability of another northern lava flow from Mauna Loa in a very few years is unfortunately indicated."

SAVING LIVES AT SAKURAJIMA

Volcanoes are not actuated by clockwork, but careful examination of their behavior over a period of time shows tendencies toward certain sequences of events separated on the average by about the same intervals, and on that basis volcanologists are becoming increasingly expert at interpreting signs and anticipating events in places which they have been able to study.

In contrast to Vesuvius in 79 and Mt. Pelée in 1902, the Japanese volcano Sakurajima was robbed of 23,500 potential

victims in 1914 because there was no reviewing board to disclaim responsibility and its warnings were promptly heeded. Sakurajima volcano forms a small island in Kagoshima Bay on Kyushu, the southernmost island of Japan's main group. It is located on the Ryukyu Rift Zone, volcanic peaks of which fringe



Location map for the volcano Sakurajima.

the Eastern China Sea. This zone is another example of the general rule of alignment of volcanoes along major abyssal cracks in the crust. The mainland islands of Japan, the Ryukyu Islands southwest, the Kurile Islands northeast, and the Ogasawara, or Bonin, island chain southward from Fuji make up over 3,000 miles of scattered volcanoes, amid hills and mountains built above the intersecting fractures which determined their location but are now concealed.

Volcanic activity seems to run in a major cycle of about 130 years in Japan as at Hawaii. In 1777–92, Oshima, an island in Tokyo Bay, Asama, about 150 miles inland northwest of Tokyo,

and Sakurajima had tremendous outbreaks. In 1908, Asama, in 1912, Oshima, and in 1914, Sakurajima repeated the series of events.

Warnings that Sakurajima was ripe for an eruption came in the form of smoke, earthquakes, and increased flow of water from springs on the mountain. Inhabitants were instructed to flee to the mainland, and the population of 23,500 was evacuated without loss of life. At 10:00 A.M., Monday, Jan. 12, 1914, an explosion opened the west side of the mountain. Ten minutes later the east side blew out, sending clouds of ash to heights of 20,000 feet. One-twelfth of the volume of the entire mountain was blown to bits.

VOLCANOES, GLACIERS, AND ICE AGES

Volcanoes and glaciers make strange bedfellows. In Iceland, Katla, after an eruption in 1823, was quiet enough to allow large quantities of snow and ice to accumulate in the vicinity. At 2:00 P.M., Saturday, Oct. 12, 1918, a series of vents along a crack trending NE-SW about 3,000 feet above sea level went into action. Great glacier-floods resulted as warm-water streams from the melting ice reached depths of over 200 feet and swept enough sand and mud down to build out the coast line. In Alaska and the adjacent Aleutian Islands are many peaks in a position to duplicate this effect.

In contrast to this, volcanoes have been charged with causing the several great ice ages which have dotted the rock-pages of geological history. It is indeed a versatile phenomenon that can make or break a glacier at will.

The process by which glaciers are supposed to have been made by volcanoes is of most immediate concern to the average world citizen, for it has operated to affect the weather in recent times. Certain volcanic vents climax periods of eruption by violent explosions. Some of these throw into the atmosphere

great quantities of such finely divided dust that from two to three years are required for it to settle back to earth. During that time, the dust spreads around the earth causing abnormal haziness, brilliantly colored sunsets, and a reduction in the amount of sun heat that reaches the ground level.

During 1783, Asama in Japan and Skaptar in Iceland erupted on a large scale. The following year average temperatures dropped below the annual mean by more than at any other time between 1750 and the present. Dry fogs in the upper atmosphere were recorded at the same time at places as widely separated as northern Africa and Scandinavia. At one place the density was such that the sun was not visible until it had reached a position 17 degrees above the horizon.

Mayon, 7,500 feet high, in southeastern Luzon of the Philippine Islands, one of the world's most symmetrical cones, erupted in 1814, as did Tambora on the island of Soembawa east of Java on Thurslay, Apr. 7, to Sunday, Apr. 17, 1815. For three days there was absolute darkness for a distance of 300 miles from Tambora. The year 1815 was noted throughout the world for long twilights and spectacular sunsets caused by the dust and became known as a "year without a summer."

In June, 1912, an observer of the U.S. Geological Survey was in Algeria making measurements on the quantity of heat coming to the earth from the sun. At the same time another observer was making similar measurements at Mt. Wilson in California. At Bassou, Algeria, during the observations of Wednesday, June 19, 1912, streaks of dust were noted lying along the horizon. These were joined by others and in a few days the sky appeared "mackereled" although no clouds were present. Finally the phenomenon became so marked that observations were discontinued. On Saturday, June 29, the whole sky was filled with haze, which continually became worse until the expedition departed on Tuesday, Sept. 10. It was supposed up to that time that the condition was local. Reports which had

reached the United States meanwhile indicated, however, that it was actually world wide and attributable to an eruption of Mt. Katmai on the Alaskan peninsula. Calculations revealed that the dust from this eruption had moved toward Washington, D.C., at a rate of 40 miles per hour, toward Algeria at 25 miles per hour, and toward Mt. Wilson at 3 miles per hour. The small velocity toward Mt. Wilson was explained by the fact that it is more nearly south of Katmai and the high-velocity winds follow a general course from east to west.

The haziness of the atmosphere during the summer of 1912 produced a decrease in direct solar radiation which amounted to nearly 20 per cent of the total heat at high sun. Reflection of the sun's rays from dust in the upper atmosphere caused an abnormal brightness of the sky in a manner similar to that by which particles of dust in a room reveal the path of a sunbeam. The dust of Katmai diminished the heat available to warm the earth by an amount sufficient to produce a fall of nearly 13° Fahrenheit in the temperature of the earth as a whole if it were effective for a long enough period of time. The fact that such a fall would leave a large section of the present temperate zones within a region of year-round ice is basis for the theory attributing glacial periods to the effects of crescendos in volcanic activity.

The Katmai eruptions produced the Valley of Ten Thousand Smokes, which has since been set aside by the U.S. Congress as the Katmai National Monument.

DISAPPEARING ISLANDS

A few of the world's active volcanoes, in building up their cones, have just reached sea level with their peaks. During a constructive period one of these may suddenly appear above the surface as an island where there had been none before. Then a destructive explosion blows off the volcano's head, the

island, and there is nothing left in sight. This mechanism produces the romantic disappearing islands of the Pacific.

Northeast of New Zealand a submarine plateau, capped by the Kermadec Islands and the Tonga Islands, is flanked on the east by two of the deepest wrinkles known in the earth's crust, the Kermadec Deep with bottom 30,000 feet below sea level and the Tonga Deep. The forces that formed those deeps have cracked the crust in several places and allowed magma to force its way upward and in places reach the surface as chains of islands which are pocked with active volcanoes. One of these at 20° 23′ S., 175° 25′ W., was called Falcon Island. Suddenly one day in 1913 it disappeared by the simple process of shooting off its mouth. On Tuesday, Oct. 4, 1927, to the accompaniment of a violent series of explosions, Falcon Island just as suddenly reappeared and remained to justify map makers.

On the northern boundary of the Pacific, a far cry from the storied South Seas, another island, Bogosloff, has been playing hide-and-seek in a similar manner. It is a member of the Aleutian chain, an arc of active volcanoes also fronting on a great ocean deep and located at about 56° N., 168° W. First reported in 1826, it has since then kept mariners and scientists busy naming new islands or mourning old, as different parts of its crater protrude above sea level following eruptions.

VOLCANIC LIGHT, HEAT, AND POWER

Proposals have often been made for the utilization of volcanic heat. This does not mean harnessing the eruptions of volcanoes, but rather making use of fumaroles, boiling springs, and heat found in volcanic districts. For many years the steam of fumaroles has been used in Iceland and Japan for heating schools and public buildings. Most of this is the steam of ground water brought to the boiling point through the agency

of underground magma or of volcanic gases, such as hydrogen, carbon, chlorine, and sulphur with their compounds, through union with oxygen of the air.

Farmers have used volcanic energy in agriculture. On the island of Ischia, near Naples, they employ fumaroles to warm tomato plants and make them sprout earlier. On the bottom of the extinct crater Agnano, a gardener is reported to have volcanic heat useful for keeping his vegetable crop producing all year. He operates an irrigation system supplied by hot springs. Volcanic steam has been used to warm hothouses where plants are cultivated.

In Iceland, North America, the tropics, and New Zealand, hot springs have been used as laundries. They have also been exploited as baths for the treatment of physical ailments.

Near Lardarello, in Tuscany, boric acid has been produced from scalding natural steam for more than a century. In 1904 Prince Ginori Conti began to operate a small steam engine by curbing a natural steam vent. Further development of the steam power was hampered by the low pressure and temperature of the surface steam and the rapid eating away of the metal by acid vapors.

In order to obtain higher pressures and temperatures, holes were drilled into the ground. These yielded a rush of steam at 375° Fahrenheit and 200 pounds per square inch pressure.

To avoid corrosion of expensive machinery, high-pressure natural vapors have been condensed under pressure, fixed gases assembled and conserved as by-products, and pure water heated above the boiling point in a low-pressure boiler to make steam. This was then utilized by expansion in low-pressure turbines.

At Castel Nuovo, a well 400 feet deep operated three turbogenerators of 2,000 kilowatts capacity. In 1929, the plant yielded some 12,000 kilowatts, and no exhaustion of the resources of the ground was apparent.

In Java, experiments at Kawah Kamodjang Crater employed a drill hole 400 feet deep, which yielded a volume of steam at 90 pounds per square inch pressure estimated capable of producing 900 kilowatts.

At the geysers in the St. Helena range in California, a great store of hot steam was revealed by drilling. It increased with depth. Borings for power found temperatures from 200 to 350° Fahrenheit and pressures from 60 to 170 pounds per square inch. The wells varied in depth from 150 to 600 feet. Temperature and pressure increased with depth. Geological conditions indicate that the region overlies intrusive volcanic magma.

VOLCANOES AS ATTRACTIVE PLACES FOR HUMAN HABITATION

Santa Maria volcano (see page 109) is the most active of five among the fifteen volcanic peaks which dominate the scenery along the Pacific coast of Guatemala, in a zone of about 16,000 square miles, approximately one-third of the republic's total area. There are many earthquakes in the vicinity. Excessively wet seasons alternate with very dry. Most of the streams are "flashy," that is, raging torrents during the wet seasons and mere trickles during dry. Deep ravines, called *barrancas*, show the destructive effects of erosion in the porous, poorly consolidated volcanic soil. Add to these conditions the threat of earthquakes, explosions, and streams of molten lava, and you do not seem to have the elements of an attractive real-estate advertisement. Similar conditions obtain in the neighboring political unit of El Salvador, yet there in an area of 13,000 square miles, about that of the state of Delaware, there are 1,600,000 inhabitants. With an average of 125 persons per square mile, this constitutes the most densely populated national area in the Western Hemisphere. Archaeological and historical records indicate that a relatively high density of pop-

ulation has obtained there for over a thousand years at least. There must be some reason.

Java is another region of volcanoes, with thirty-two more or less active, including Krakatoa in the strait separating it from Sumatra (see page 96). About 19,000 of its 48,000 square miles, approximately the area of New York State, are under cultivation and support 40½ million persons, more than 650 per square mile. This makes it the most densely populated area of the globe, and it is a strictly agricultural country.

An explanation lies in the fact that, while the violent manifestations of nature are spectacular and widely publicized, their regions of direct total destruction are very limited, and certain indirect results place the vicinity in a condition highly favorable to agriculture. The plains and mountain slopes of western Guatemala, El Salvador, Java, and similar regions, are characterized by luxuriant vegetation, which shows them to be regions of great fertility. The high peaks reach into progressively cooler zones where crops flourish which could not be grown in the lowlands. Volcanic eruptions renew the soil near by. In Guatemala, the materials erupted are in dust clouds and clastic flows, with pumiceous texture dominating. Chemical analyses show fairly small amounts of common plant nutrients such as potash and phosphates, but the loose texture permits abnormally rapid decomposition by atmospheric agencies. Rain water is quickly dispersed through the porous soil, but this is an advantage, for less pervious material would become unworkably boggy in the excessive rainfall of the wet season. Products of decomposition accumulate to reduce porosity downward, and here crops flourish as overlying material delays drying out of the soil during the dry season. An eruption of Fuego during the dry season of 1932 covered the slopes of the volcano with coarse ash to a depth of about 10 inches. Three weeks later, vegetation which had escaped destruction by burning was putting forth foliage vigorously as the ash covering protected the soil's moisture content.

Natives long ago learned that corn planted in the soil below this ash sprouted promptly and grew rapidly. Coffee planters in both El Salvador and Java have frequently observed that the coffee crop is larger the year after an eruption, and this has been attributed to the action of ash in conserving soil moisture during the dry season.

The versatility of Guatemala is evidenced by the production of sugar cane, bananas, and black beans in lowlands, coffee on the temperate slopes, sheep and wheat on elevated plateaus subject to occasional frost, and maize at all elevations up to 7,000 feet.

The volcanic soil of Java differs from that of Central America. It is derived from iron-rich basaltic lavas. Much of the soil has been brought down from the steep slopes of the volcanoes and deposited on the plains. It decomposes to a clay-rich but pervious combination which retains moisture during dry seasons. It contains fair amounts of potash and phosphates and is being constantly renewed by volcanic activity.

Scientific development of the resources of Java by the Dutch is largely responsible for the region's ability to support such a large population. Efficient systems of terraces in the embayments of volcanoes reduce soil erosion and contribute to the unique appearance of the landscape. The necessities of water supply have made the hydrological service one of the most important on the island. A unique achievement of this service was the treatment of acid waters issuing from the crater lake of Kawah Idjen and destroying vegetation and crops. In the valley below the crater was found a stream which was sufficiently alkaline to neutralize the acids from Kawah Idjen. The waters resulting from the joining of these streams became available for irrigation.

CRATERS OF THE MOON

Volcanoes contribute symmetrical peaks to the mountain scenery of some parts of the earth. They are believed by some to have been responsible, also, for many surface features of our nearest celestial neighbor, the moon, but that explanation of the craters of the moon is very doubtful.

The moon's diameter of 2,000 miles is about one-quarter that of the earth. It is 240,000 miles from the earth, but even at that distance some of its principal markings can be seen with the naked eye, and all of them are clearly visible in a relatively low-power telescope. Large dusty patches are so located as to cause the moon to resemble a man's face to imaginative eyes. In a telescope, these take form as extensive plains, which were originally thought to be seas and were named accordingly. Subsequent discovery of permanent elevations and depressions in these areas eliminated the possibility that they are seas, and it is now known that the orb cannot retain either water or an atmosphere like the earth's.

Bordering certain of these plains are a few mountain ranges, of which three are most notable. They have been named the Apennines, the Caucasus, and the Alps. The Apennines are about 450 miles in length, and some of the peaks tower to 20,000 feet above the neighboring plain in what must be a scene of gargantuan grotesqueness viewed from the lunar surface. The Alps are split by a flat-bottomed valley 6 miles wide and 75 miles long bordered by mountains 10,000 feet high. Jagged cracks or chasms trace across some of the plains.

The lunar scenes are dominated, however, by craters which have given rise to suggestions of volcanic origin. They range in diameter from 1 to 150 miles and vary greatly in structure and arrangement. Some are elevated above their surroundings, others are depressions with low surrounding ramparts, and still others are like walled plains. Some are isolated, like the vol-

canic islands of the Pacific, while others are crowded together to the point of overlapping each other. Copernicus is one of the finest craters. Though its diameter of 46 miles is exceeded by others, its location near the center of the disk, which permits thorough examination and its towering rampart rising 12,000 feet above a great inner plateau featured by a group of three cones 2,400 feet high mark it as unique. Many ridges lead away from the outer rim of the main crater.

Radiating from Copernicus and several other large craters, a great many bright streaks may be seen at full moon. They do not have a definite outline and do not appear to protrude from the surface. Their courses are not affected by the topography as they traverse craters, mountains, and plains. One description says: "They look as if, after the whole surface of the moon had assumed its final configuration, a vast brush charged with a whitish pigment had been drawn over the globe in straight lines, radiating from a central point, leaving its trail upon everything it touched, but obscuring nothing." It has been suggested that these streaks are dikes of intruded matter which reflects the sunlight more effectively than the surrounding rock.

The crater most conspicuously marked by these streaks is Tycho. It is 54 miles in diameter, 16,000 feet deep from top of outer rim to level of inner floor, from which there rises a 5,000-foot central cone.

Alternative to the theory that the moon's craters are dead volcanoes is the proposal that they were formed early in the satellite's history when it was still plastic and was subjected to bombardment by great masses left over from the chaos of creation of the solar system. This idea finds support from craters which are great in diameter but low or entirely lacking in height above their surroundings. Some or many of the bombarding fragments may have exploded as they penetrated the moon's surface, to combine the external effects of volcanic explosion and falling body impact. At any rate, scientists are still arguing

about the whole thing. Maybe some future rocket trip to the moon will give us a solution based on field data.

THE GRAND FINAL CATASTROPHE— "END OF THE WORLD"

Thus the moon, tied to our earth by a thing we call gravity, swings through the heavens with us as a museum of fossil volcanolike craters brought into the solar spotlight once a month. Its supply of internal heat appears to be completely exhausted. It is a dead, cold thing, but speculative science has assigned to it one last role in the creation of catastrophe on a stupendous scale. As the brake of tidal friction has already brought the moon to a point where it now turns only one hemisphere toward the earth at all times, so it will gradually exhaust the earth's energy of spin until it and the moon each rotate once in forty-seven of our present days and the moon revolves once around the earth in the same length of time. By that time, the moon, which throughout geological time has been slowly receding from the earth, will be much farther away than it is now. Then it will slowly return toward the earth, starting some 45 billion years from now (the earth's present age has been estimated at over 3 billion years). When it gets to within about 11,000 miles (2.86 times the earth's radius, to be exact), tides within the moon will cause it to burst apart. The myriads of fragments from this explosion will carry on where the moon as a whole left off and continue to revolve around the earth, spreading into a gigantic ring of stones and boulders. Many strays will probably bombard the earth for a time. The limit to which a satellite can approach its planet was computed theoretically by Edouard Roche in 1848. Phobos, a satellite of Mars, is near that limit now. One or more satellites of Saturn have actually been trapped and the fragments from their disruptions form the famed rings of Saturn.

CHAPTER 4

Mountain Making as the Cause of Earthquakes and Volcanoes

Earthquakes and volcanoes are effects. Their distribution and something of the mechanism by which they operate have been discussed. Earthquakes are the vibrations produced by breaking of the earth's crust. Volcanoes trace their existence to abyssal fractures in the crust. But why all these cracks?

Both phenomena are intimately connected with processes by which mountains are made. Volcanoes are mountains of a kind, in the popular sense of the word, but in true perspective they are, with some exceptions, only festering wounds on the backs of true mountain ranges.

The nature and origin of sedimentary rocks have been mentioned briefly. From the manner of their accumulation, it is apparent that they will ordinarily occur in layers. For this reason, they are called *stratified rocks.*

Normal irregularities of individual strata are increased by the fact that land and water levels of the globe are continually changing with reference to each other. As a result, an area of deposition under shallow-water conditions may gradually become one of deep water, or the reverse. Slow sinking of a region of accumulating sediments makes possible the piling up of sedimentary formations to thicknesses exceeding many fold the depth of water at any one time. Later elevation of the same region leaves above sea level the rocks that were formed under water.

The principal mountain ranges of the world, old and young,

include great masses of sedimentary rocks. In the Appalachian Mountains of the eastern United States have been found sediments the thickness of which probably exceeds 35,000 feet; in the Wasatch Range of Utah, 30,000 feet; in the Coast Ranges of California, 30,000 feet; in the Alps of Southern Europe, 50,000 feet. Here we have observed facts which require explaining. *The highest land on the globe today was sea-bottom stuff at an intermediate stage in its career.*

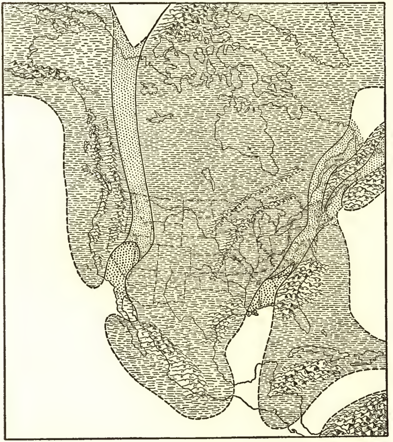
In the study of earth history, it has been found necessary to establish an arbitrary time scale by which to date the complex series of events with reference to each other. At various times, attempts have been made to assign a number of years to the arbitrary intervals thus established. Some recent efforts in that direction have been based upon the determination of lead-uranium ratios which indicate the lengths of time during which uranium has been breaking down to lead through radioactive emanations. Some of the oldest rocks studied appear to be of the order of 3 billion (3×10^9) years old. The time between their formation and the present has been divided by geologists in a timetable by which major events are dated.

Evidence of a universal mobility of the earth's crust is found in the fact that every continent has a veneer of sediments, showing that land which is now above sea level was once the scene of the deposition of sediments underwater, in shallow inland seas or other bodies. North America has been invaded by oceans to a greater or less extent on numerous occasions since Pre-Cambrian time. The sedimentary rocks formed during these invasions are now found at varying heights, sometimes warped into attitudes considerably inclined to those in which they were deposited.

The most striking of all evidence pointing to mobility of the earth's crust, however, is found in mountain ranges. In a general way, many have had histories which involved the same broad divisions: (1) deposition of thick lenses of sediments on

THE GEOLOGIST'S TIMETABLE

Eras	Periods	Mountain-making episodes	Life	Years B.C.
CENOZOIC (Recent life)	Recent	Himalayas	Age of Man	25,000
	Pleistocene (Great Ice Age)			2,000,000
	Pliocene		Age of Mammals	
	Miocene	Alps		35,000,000
	Oligocene			
	Eocene (Dawn of recent)			60,000,000
MESOZOIC (Middle life)	Cretaceous	Rocky Mts.	Age of Reptiles	
	Jurassic	Sierra Nevada		
	Triassic			
PALEOZOIC (Ancient life)	Permian	Appalachians		205,000,000
	Carboniferous			300,000,000
	Devonian		Age of Fishes	
	Silurian	Scottish Highlands		450,000,000
	Ordovician		Age of Invertebrates	
	Cambrian			600,000,000
PROTEROZOIC		Younger Laurentians		
ARCHEOZOIC		Older Laurentians		2,000,000,000
Oldest rocks by radioactive mineral analysis about 3,000,000,000				



The probable geography of North America in Lower Cambrian time. Inland seas are dotted; land areas are shown by dashed, wavy lines; drainage is unknown. There was little or no vegetation, and the climate was mild and relatively arid. Corals flourished in the waters of what are now temperate and polar regions. (After Schuchert)

the continents in ocean-filled troughs, known as *geosynclines;* the assemblage of sediments is called a *geosynclinal prism;* (2) folding and faulting caused by essentially horizontal compressions, the general result being a shortening of the crust; (3)

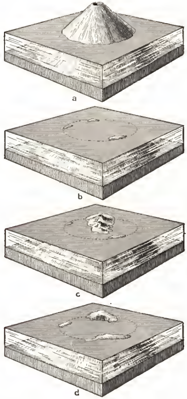
elevation of the folded and faulted sediments; (4) intrusion of magma into the core of the range; (5) penetration of basalt into the near-surface crust, and extrusion of it through volcanic vents; (6) removal of elevated rocks by erosion; (7) renewal of folding, elevation, and erosion, sometimes but not necessarily preceded by further deposition of sediments on the beveled surface of the earlier mountains.

The height of a mountain range is, in a rough way, inversely proportional to the age of its folding. The Himalayas, folded in the Pliocene, are at heights of 30,000 feet today. The principal events leading to the formation of the Alps occurred in the Oligocene, and they are now 15,000 feet high. The greatest folding of the Appalachians came in the late Paleozoic, and the maximum elevation today is 6,700 feet. Late Pre-Cambrian mountains north of Lake Huron are only 1,500 feet high. In this sense, present mountain ranges are sometimes called young or old, regardless of the absolute age of the sediments of which they are composed or the number of times they have been through the mountain cycle.

One striking observed generalization about mountains is that folding and elevation are essentially independent events, in spite of some possible overlapping. *In other words, mountain structures, that is, folded and faulted sediments, may be formed or forming below sea level today.*

All high land is not underlain by folded mountain-structure sediments. The Berkeley Hills and adjacent ranges near San Francisco consist of sedimentary rocks which were once practically horizontal layers of sea-bottom deposits but are now intensely folded and faulted. In contrast to this, plateaus may be elevated without much disturbance from their original attitude. Erosion, carving into such strata, produces mountainous relief, as in the Grand Canyon of the Colorado River.

Intermediate between these extremes are the Jura Mountains of Switzerland, where simple structures and symmetrical folds are found.

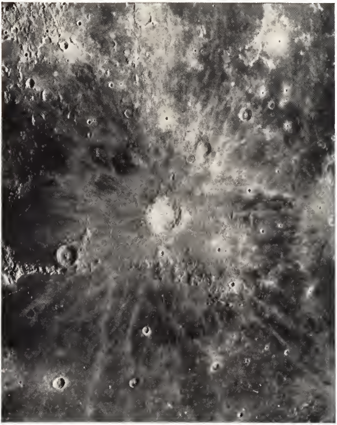


Disappearing islands illustrated by stages in the history of Krakatoa. (a) Hypothetical central cone of andesite which existed at one time; (b) disappearance of the cone, possibly through subsidence, leaving three islands where there had been one; (c) building of the basaltic cone of Rakata and the andesitic cones of Danan and Perboewatan, which combined to form the island of Krakatoa; (d) remnants after the explosion and further subsidence in the central area, of Monday, Aug. 27, 1883. (After B. G. Escher)

Nature's atomic bomb — the cloud of an erupting volcano.

A lunar landscape, showing craters and a mountain range with peaks rising to 20,000 feet. Owing to the absence of an atmosphere, stars are visible in full daylight. (After Gillet and Rolfe)

Craters of the moon. Southern area in last quarter. (Photo by Mt. Wilson Observatory)



The giant lunar crater, Copernicus and radial streaks. Moon past last quarter. Copernicus is 46 miles in diameter, with a rim rising 12,000 feet above the surrounding plain. (Photo by Mt. Wilson Observatory)

The history of the Alps themselves has been amazingly complex and records buckling of the crust on a gigantic scale. The folded and overturned beds that best illustrate the effect are those called *nappes*. It has been computed that a block which

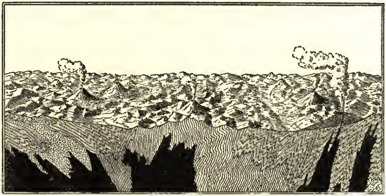
Relief map of North America.

was originally 750 miles across was compressed until it is now 100 miles.

On the other hand, the deposition of a prism of sediments in a structural trough has not always been followed by mountain making, as illustrated by a stillborn range under part of the state of Michigan.

A glance at a relief map of the United States reveals a broad zone of mountains from the west coast inland over nearly

four-tenths of the continent's width and a much narrower band near the east coast. These actually consist of several groups of mountains, each of which has had a history more or less independent of the others. Just as we cannot, on geological grounds, lump mountains together just because they happen to be in



A Late Paleozoic landscape in the vicinity of the present Connecticut River, showing the "New England Alps" of those days.

the same general vicinity, so has it been found impossible, thus far, to construct a broad, general theory concerning their origin without leaving unaccounted for about as many facts as are explained. Science is like that sometimes.

One thing is clear, however. The geological record is everywhere one of ceaseless change, of forces at work throughout geological time and today, of blocks of the earth's crust, small and large, grinding, grating, tossing about under the urge of unseen, unexplained internal forces.

The California Coast Ranges, Sierra Nevada, Basin Ranges, and scores of other mountains on every continent represent what are commonly called *young mountains.* They are the scene of many modern earthquakes and volcanoes. This relationship, in fact, has made popular the generalization that the

world's earthquakes, with rare exceptions, cluster in the zones of young mountains such as those. In contrast, regions of older mountains, the Appalachians, the Harz, the Ural, the Altai, passed through the acute stages of youth in the geological middle ages. It is easy to regard them as worn-out oldsters incapable of further frivolities, hence unlikely to cause earthquakes as they did by the faults of their earlier years. Here again may be seen the dangers of too hasty generalization, too earnest a search for a broad, simple formula to guide us in attempts to catalogue future possibilities on the basis of present experience.

THE GREAT ICE AGE

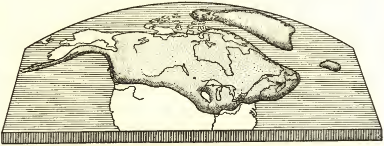
The most recent geological event of great importance in the northern Appalachian region, as well as throughout the Great Lakes district and adjacent portions of the United States and Canada, occurred during the great ice age, when vast sheets of glacial ice formed over the land, melted away, and spread again four times. The Great Lakes, Niagara Falls, and many of the present topographical characteristics of these regions trace their origin back to the last sheet of this ice age.

The weight of the ice in a continental ice sheet such as those of the Pleistocene glacial stages is sufficient to cause the crust to sink beneath its burden. When the ice melts, the depressed crust recoils to something like its original position, albeit pretty slowly.

"Modern" sea beaches of loose sand and gravel, with shells of animals identical with living forms, geologically so young that erosion has not had time to demolish them, are found today at varying heights above present sea level in some of the glaciated tracts. They supply a scale by which to measure the recoil, chiefly around the Scandinavian peninsula and northeastern North America. These changes of level have occurred, presumably, within the past 25,000 years, and the upward move-

ment may be still continuing today. In the Great Lakes region, it has been found from analyses of water-level records that the land surface is teetering from north to south at the rate of about 6 inches per 60 miles per century.

One guess, already mentioned, as to the cause of northeast-



The most recent ice sheet over North America.

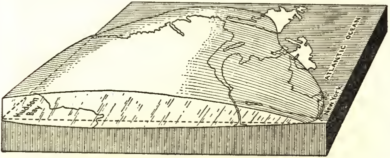
ern America's earthquakes is crustal recoil following the melting of the last glacier. The data to substantiate such a guess, however, are very meager, and many point equally well to deep-seated forces related to old mountain-making and crust-heaving activities and causing displacements along ancient scars.

SUMMARY OF MOUNTAIN MAKING

Wherever the data of geology have been interpreted, they point to a continuous heaving and settling of the skin of the globe. In terms of the human life span, the movements are slow, their manifestations intermittent. The zones of most acute instability migrate, from period to period, but even an area like the Appalachians, where the first mountain folding occurred during the geological dark ages, in the Paleozoic era, has not achieved a condition of quiescence.

The forces which squeeze and distort miles of rocks, which push to heights of thousands of feet blocks of the size of the

Coast Ranges, Sierra Nevada, Inyo, or any mountain range ever known, stagger the imagination. Yet not the least strange of the factors involved are the relatively small dimensions of areas which undergo deformation so nearly independent of the surroundings.



Bending of the crust under an ice sheet.

An outstanding feature of mountain making is the extreme complexity of the processes. Troughs accumulating sediments are never at rest; repeated uplift and depression visit the regions. Some sediment-filled troughs become mountains; others do not. On the basis of past history, we should expect that existing basins of sedimentation are in motion. Mountain-making forces have not been confined to the borders of the present deep sections of the permanent ocean basins and are not necessarily so related today. Extending over 1,000 miles southwestward from north of Lake Huron into the interior of the continent were the "lost mountains of Wisconsin," or Killarney Mountains, believed to have rivaled the present Alps, our perennial yardstick for something pretty large in the way of mountains.

To get into a proper frame of mind for reviewing guesses seeking to explain the ultimate cause of mountain making, it is desirable to consider first some 1947 ideas about the origin of

the earth. Then we may well decide this thing has gone far enough. In fact, we may find there is no farther to go.

Here, naturally enough, we dip into the realm of astronomy, since the earth is merely a dying cinder, a casualty of the second law of thermodynamics in the dead, cold interstellar space of the macrocosmos. Once more we find many clues, facts that must be accommodated, but no answers. Astronomers, able to see less than 1 per cent of the universe about us, have performed miracles. They have even calculated that there are 10^{11} (1 followed by 11 zeros) galaxies, more than 10^{22} stars, and something like 10^{79} atoms in a universe which weighs 10^{55} grams. At the same time, they are in some ways as interested in the earth as any geologist, for the more they delve into the problem of its origin, the more they find that this involves processes which are universal. The earth apparently supplies us with hand samples of the principal components of the universe. Astronomers identify these elements by lines of the spectrum of light which comes to us through space from other members of the universe. They find, however, that such lines are shifted toward the red part of the spectrum in a way interpreted to mean that the light sources are moving away from this part of space. The ones now farthest away are moving fastest. Working the present distances and speeds of recession in reverse has led to the fascinating discovery that the stars and galaxies of our known universe were pretty much bunched together about 3 billion years ago. In fact, that is about as good a number as can be pulled out of the astronomical hat today for dating the catastrophic, explosive emergence of our universe from the chaos that must have existed if all its 10^{79} atoms were once the giant "cosmic atom" of Lemaître or even if they were in discrete but relatively closely packed blobs.

If this date of 3 billion years ago continues to find support from astronomical lines of evidence on the origin of the universe, it would seem to be more than coincidence that the

oldest rocks on the earth are found to contain products of radioactive decay indicating that their minerals took solid form about 3 billion years ago. Following this trend of the data to its logical conclusion, Harvard's astronomer Harlow Shapley in 1932 "despairing of our finding an acceptable orderly theory of the origin of the planets . . . proposed an alternative that cannot be easily disproved. It might be called the hypothesis of the chaotic origin of the solar system. It ties in earth-birth with the genesis of stars. . . . On the chaos hypothesis we assume that whatever collisional or explosive event produced the sun also simultaneously produced a very large number of fragments." By a process of dynamical elimination of the unfit, these fragments were reduced in number until only a few rightly spaced and oriented ones survived to become our planets.

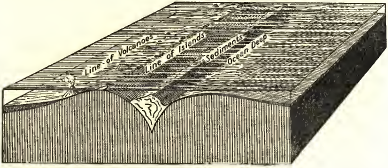
Shapley warns us: "We should remember that the hardest problems of cosmogony would not necessarily be disposed of even if we should get a satisfactory theory of the origin of the earth. For we would ask at once concerning the origin of the sun and of galaxies and eventually be driven back to the deeper puzzles of the origin of matter, origin of space, of time, and of origins. Planetary genesis is therefore only a decoy, leading to universal processes."

Comets and meteorites are part of the debris of "creation," just as is the earth.

The knot destined to become our earth quickly began to form a crust, but while still liquid, its heavier constituents congregated near the center to form the supposed nickel-iron core which does things to earthquake waves.

Cooling went on apace, and finally a crystalline crust a few tens of miles thick had been formed. As the entire globe cooled slowly but surely, it tended to shrink in size. This buckled the brittle outer crust until parts protruded above the oceans, which had formed as soon as temperatures permitted condensation of steam, and continents came into existence.

The mechanism by which cooling goes on in the deep interior is actually the key to one picture of the ultimate cause of mountain making, earthquakes, and volcanoes. If a substance which can flow, no matter how stiffly or slowly, lies between a region of high temperature and one of low, it attempts to transfer heat from the one to the other by convection currents.



Buckling of the crust by convection currents.

In contact with the hot layer, it warms, expands, and starts to rise. When it reaches the cooler layer, it cools, contracts, and starts to sink. Over wide areas this is accomplished by a series of cells, each of which includes two closed loops of circulating matter.

Such currents impinging on the earth's outer crust are pictured as bulging it above the rising currents, depressing it under the sinking, and tending to drag the crust horizontally toward the sinks to form roots for mountains. The motion would be complicated by the formation of vortices and by uneven distribution of heat caused by radioactivity serving as an extra furnace in some places.

One series of investigations has resulted in a proposed explanation of certain conditions in the West Indies in terms of a local downbuckling of the crust. The volcanoes of that region are pictured as riding near the crest of one of the buckled

limbs. They include Mt. Pelée, which destroyed St. Pierre in 1902. Earthquake sources are not distributed so systematically with reference to this downbuckle.

Once sections of crust have reached lower, hotter levels, either by downbuckling or by simple foundering when pushed

The Guadeloupe-Martinique chain may be riding on a convection bulge.

under a geosyncline, they gradually warm up and melt, expanding as they do so. This forces upward the previously folded sediments above and supplies a mountain range with its height. At the same time, some of the melted and expanded material eats its way into the core of the range as a batholith. The entire process would probably lead to the formation of abyssal cracks in the crust, through which basalt could work its way into the picture.

Mountain Making and Volcanoes in the Pacific

In recent years, the world has become increasingly aware of the Pacific Ocean area. During World War II, thousands of people visited its far reaches for the first time, and following it, other thousands will. The region is today the greatest laboratory in the world for a study of earthquakes, volcanoes, tidal waves, typhoons, and mountains in the making. In fact, man's very existence there depends upon a thorough understanding of those phenomena.

PACIFIC MOUNTAINS—"CONTINENTAL" ISLANDS

To the north, west, and south in particular, the Pacific is bounded by mountain ranges in varying stages of active growth. A striking feature of their distribution is their arrangement in a series of arcs with great ocean deeps on the convex outer rim, a string of islands topping shoal water back of the deep, and a relatively shallow platform attaching the shoal to the permanent continental mass behind it.

One such arc forms the Aleutian Islands. If the point represented by 62°40′ N., 178°20′ W., is located on a 30″ globe and used as a center, a circle of radius 760 statute miles starting at Komandorskie Island will exactly define the axis of the Aleutians for 1,450 miles to the Alaskan peninsula. Fronting this on the Pacific side is the Aleutian Trench, 2,200 statute miles long, 50 to 100 miles wide, with a maximum depth of just over

25,000 feet. The nearest land rises 32,000 feet above the deepest part of the trench. Back of it is the Bering Sea, a flat-bot-

Arc formed by the Aleutian Islands. The center is at 62° 40′ N., 178° 20′ W.

tomed, relatively shallow body of water, over half of which is less than 100 fathoms (600 feet) in depth. The deeper parts of this basin slope southwestward. Projecting from the Aleutians

into Bering Sea from just north of Amchitka Island is a submerged mountain range curving on an arc with a radius of 125 miles for a length of 600 miles. It stands 12,000 feet high, 60 miles wide, and rises to within 450 feet of the surface of Bering Sea, to form Bowers Bank.

Another famous arc is that of the main islands of Japan. From a center at 42° N., 130° E., an arc with radius 650 miles roughly defines the Pacific side of the islands, although structurally it is a blend of two primitive arcs. Offshore from the northern part of this arc lies the 25,000-foot Tuscarora Deep, which actually is part of the Japan Trench that extends northward to front also the arc of the Chishima (thousand islands—Kurile Islands) and southward along the Shichito-Marianas arc where it includes the 34,625-foot Ramapo Deep. (The "shichi" of Shichito is Japanese for "seven" and is pronounced with almost complete disregard for the first "i," as "shhh-chee." Shichito, then, is "shhh-chee-toe.")

In the South Pacific, arcs of this kind continue, but many islands of another kind come into the picture to confuse one who takes a casual glance at a map. They fall into two definite groups on the basis of geographical distribution as well as chemical analysis of materials erupted by the many volcanoes scattered among them. One group is genetically related to continental rock masses, and the other consists of true deep-sea islands.

Igneous, or "fire-made," rocks are mixtures of minerals solidified into crystalline units from a molten mix. The bulk of the igneous rocks of the globe belong to two types already discussed, granite and basalt. Granite is an intrusive rock. It has been injected in great volume into crustal masses which protected it as it cooled slowly to the familiar coarse-grained form later exposed as erosion stripped off the cover. Granite and rocks derived from its disintegration and reassembly by sedimentary processes dominate the continents of the world. In

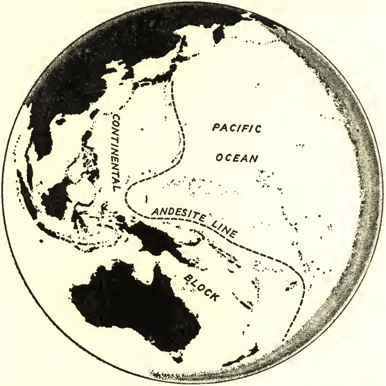
contrast, basalt is extrusive. It has reached the surface through volcanic vents and deep-seated fissures. When basalt has to penetrate a granitic "continental" shell to reach the surface, it is sometimes contaminated or diluted by granitic components and a hybrid type comes out. One of the most common of these in the Pacific is called *andesite*. Diagnostic differences among these types are the percentages of their composition devoted to silica (SiO_2) and to one of the crystalline forms of silica, quartz:

	Per cent silica	*Per cent quartz*
Granites	70	25
Andesites	60	15
Basalt	50	0

When granite, granite derivatives, or andesites are found on islands, they are classed as "continental," that is, resting on a platform of dominantly continental rocks. On this basis, the rim of the Australasiatic continental mass is defined.

The outermost arcuate continental-rim islands swing from Japan through the Idzu Shichito (Seven Idzu Islands), Ogasawara (Bonin), Kazan (Volcano), Marianas, and Palau groups to the border of the Netherlands Indies, where they turn eastward, then southeastward along New Guinea, New Ireland, the Solomon and New Hebrides groups. After including the Fiji Islands, the line swings sharply southward, including, among the continental islands, Horne, Tafahi, Niuatobutabu, the Tonga and Kermadec groups, and New Zealand, but excluding Wallis, Niuafou, and the Samoan Islands. This defines the border of the true Pacific basin and has been called the "girdle of fire" because of the extent of volcanic activity which it includes.

These islands are peaks on major mountain ranges towering above the ocean floor, writhing with manifestations of youth.



Andesite line dividing the Australasiatic continental block from the true basin of the Pacific Ocean.

DEEP-SEA ISLANDS

Within the Pacific basin itself, there are still other island mountains of a different type. In general they are chains strung along abyssal fissures in the earth's crust through which basaltic lavas have poured to build up piles and ridges on the deep

ocean floor until the tops appeared as mountains. For the most part they have a northwest-southeast trend, and all are characterized by the absence of rocks of continental types. The most majestic and clear-cut of all is the Hawaiian chain, extending from worn, inactive remnants of earlier volcanoes at Ocean and Midway through a series of reefs, pinnacles, and small islands southeastward to the main group, including Kauai, Oahu, and Maui. It terminates in the highest deep-sea island in the world, Hawaii, which stands 30,000 feet above the adjacent sea floor and is still growing as lava wells from the southeastern end of the crustal fissure. The Hawaiian ridge is 1,500 miles long.

A similar alignment is shown by the islands of Samoa, closest of the deep-sea groups to the Australasiatic continent. Savaii, on the northwestern end, is the "Hawaii" of Samoa. The islands decrease in size and height southeastward through Tutuila, with its famed Pago Pago Harbor, to Rose Atoll, which caps a truncated volcanic cone as do the Midway and Ocean islands of the Hawaiian chain. On a prolongation of the axis of the islands of Samoa lie the Cook and Tubuai chains. The Cook-Tubuai line is about equal to the Hawaiian in length. Northeast of this, and parallel to it, is a line including the Society (with Tahiti) and Taumotu groups, with Pitcairn Island near its southeastern limit. Another pronounced alignment is shown by the islands of the Marshall, Gilbert, and Ellice groups.

The structural affinities of such groups are clearly shown on a map such as the *National Geographic Magazine*'s "Pacific Ocean," where ocean depths are contoured. There the numerous islands that to the casual observer look like so many random dots on an ordinary map appear in their true relationship as high points on broad, extensive ridges rising above the ocean floor.

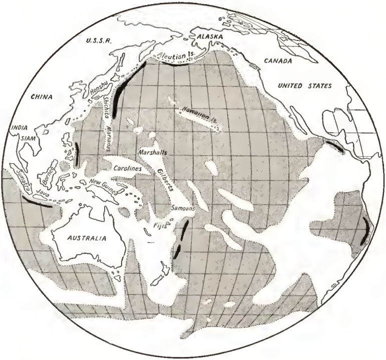
CORAL ISLANDS

No discussion of volcanic islands is complete without the inclusion of coral islands, for these are all volcanoes at heart.

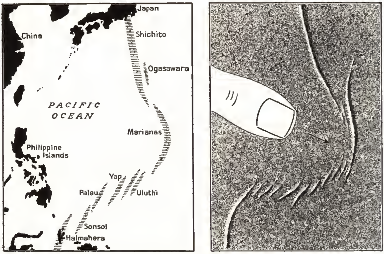
Within about 30 degrees north and south of the equator, in clear water at about 68° Fahrenheit, certain corals and related organisms built calcium carbonate reefs down to depths not exceeding about 100 feet. This limitation upon depth requires that they start from a previously erected platform if they are to reach the ocean surface in the deep waters of the Pacific, Indian, or Atlantic oceans. Volcanoes supply the platforms. The reefs may form offshore as barriers surrounding a central mass of other rock or along the shore as fringes around the other rock, but the most picturesque of all are those which form coral atolls where coral or coral derivatives are the only materials above sea level.

Viewed from the air, an atoll is a narrow, closed, irregularly curved band of startling aquamarine color where the water of the deep ocean suddenly shoals. Scattered along the band are small patches of dry land standing a few feet above sea level. This ring encloses a region of relatively shallow water, called *lagoon*. The preference of corals for clear water causes them to cluster around the edge of a volcanic platform and to grow only indifferently, if at all, where the lagoon waters are muddied by storm waves.

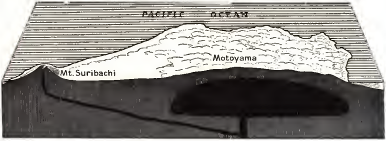
During the last ice age, quantities of water were drawn off from the oceans to form the icecaps. As a result, sea level was lowered by something like 250 to 300 feet. The more frigid global climate also cooled waters to the point where some which once supported coral growth could no longer do so. As water began to return, sea level started upward once more, and temperatures rose, drifting coral and related animals gained a footing and thrived. Under favorable conditions, growth easily kept pace with rising water. Thus, in the tropical ocean waters



Depth pattern of the Pacific Ocean. Shaded zone between 12,000 feet and 20,000 feet in depth. Solid black areas greater than 20,000 feet in depth.



Laboratory experiment which produces folds similar to those of the Shichito-Marianas chain. (After Tokuda)



Iwo Jima's volcanic features.

The trough of low pressure which lay in the path of the New England hurricane of 1938. (After Time)

Grand Canyon of the Colorado, carved in part from essentially flat-lying beds. (*From* Aspects of the Earth, *by N. S. Shaler, published by Charles Scribner's Sons, 1890*)

of the world there developed clusters of remarkably similar atolls and modified atolls with lagoon depths surprisingly uniform, rarely exceeding 300 feet, the depth planed by waves of the low sea level of the ice age.

A special case of growth on a volcanic platform is the island of Bermuda in the Atlantic Ocean. It is perched on the principal peak of an ancient volcano, with near-by shoals representing parasitic cones and part of the platform under a cover of water sufficiently shallow and protected to serve as shelter for myriads of marine plants and animals. Recorded in the soils of Bermuda are four intervals of rigorous climatic conditions during the most recent great ice age, when the average temperatures must have been far below the present comfortable levels. Examination of these soils shows that at least several score thousands of years have passed since the volcano's last eruption.

In the Indian Ocean, there are many coral atolls in the Laccadive and Maldive groups, which top a submarine ridge extending southward from India. The Seychelle Islands, Saya de Malha, Nazareth Bank, Mauritius, and Réunion outline an arcuate submarine ridge.

The coral islands of the Pacific are almost countless. The Caroline, Marshall, Gilbert, and Ellice groups are merely random samples which contain many islands.

A great many, if not most, of the coral islets of the Indo-Pacific probably would not be in existence today had it not been for a world-wide lowering of sea level, amounting, according to various estimates, to from five to some tens of feet during the past 3,000 to 4,000 years. Some of these have undergone sinking or elevation from various independent local causes.

In general, no single theory covers the facts in explaining coral reefs. No attempt should be made to force them all into a single pattern.

JAPAN

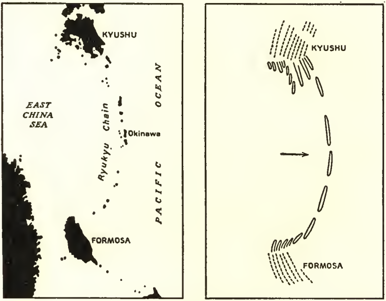
When arcuate mountains are examined in close detail, it is found that the circular or smoothly curved arc description is an oversimplification. Small subunits are actually strung along the main arc en echelon, that is, each substructure is lined up in a direction which is slightly oblique to the general line of the main arc.

According to present beliefs, the region around the present main islands of Japan was relatively stable and at rest about 50 million years ago. Then, forces operating from the direction of the Asiatic continent and centered in the vicinity of the present Marianas wrinkled the crust into a giant arc composed of the elements Shichito, Ogasawara, Marianas, Ulithi, Yap, Palau, Sonsol, and Halmahera groups, strung along it en echelon. A similar effect can be produced by placing a sheet of coarse-textured paper on a glass plate, coating it with a thin layer of paste, placing a finger on it, and pushing gently. The pattern of folding can be varied in this experiment by rotating the finger as it pushes—allowing part of the paste-soaked paper to dry, representing a stable land mass, before adjacent wet portions are folded—and in other ways.

Later, a similar shove against northeastern Japan bowed it toward the Pacific. The rocks at the junction of these two arcs were particularly distorted and now form what is structurally known as the Fossa Magna, or Big Ditch, of Honshu. This Big Ditch cuts across Honshu from the Japan Sea and comes out on the Pacific side at the Idzu Peninsula and Sagami Bay. It is the scene of considerable volcanic activity, including famous Fuji, and of many major earthquakes, including the catastrophe of Sept. 1, 1923.

Southwestern Japan then became involved as a buttress for a push from the East China Sea, which formed the Ryukyu arc. Formosa stood as the southern buttress of the Ryukyu arc and

as the tortured junction between it and an arc to the south swinging through Babuyan Island into Luzon of the Philippine Islands.



Forces that developed the Ryukyu chain between buttresses formed by Kyushu and Formosa. (After Tokuda)

MODERN TRAILS ACROSS THE PACIFIC

Before World War II, Pan American clippers flew regular schedules across the Pacific. One of the main routes went from Manila via Guam, Wake, Midway, and Oahu to California.

GUAM is perched on top of the ridge folded in the formation of the Shichito-Marianas arc, which extends from Japan to Halmahera. It is the largest and most important of the Marianas. It has an area of about 225 square miles and lies between latitudes 13°14′ and 13°39′ N., longitudes 144°37′ and 144°58′ E.

Guam lies in a region of major earthquake activity and on Monday, Sept. 22, 1902, one destroyed every masonry house on the island. It is also in the hurricane belt (see Chap. 7). The first catastrophic hurricane of which we have a record for Guam was on Sept. 8, 1671, during a pitched battle between Spaniards and native Chamorros. The record picks up again with exceptionally severe ones: August, 1848; September, 1871; November, 1895; May and November, 1900; August, 1902; November, 1914; July, 1918; October, 1924; November, 1940.

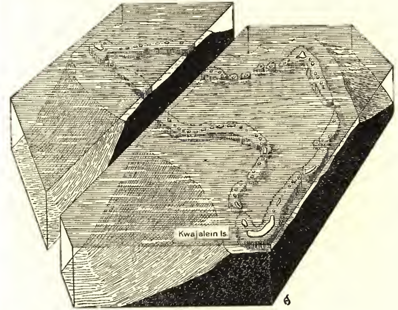
WAKE ISLAND is a section of a partially "elevated" atoll centering near 166°35′ E., 9°18′ N. It is 1,505 statute (or aviation) miles northeast of Guam's Clipper base. Other sections of the atoll's bounding reef which are above sea level are Peale Island and Wilkes Island. The lagoon is very shallow and useless for large shipping. The volcano supporting Wake appears to be relatively isolated, although it may be structurally related to some submarine peaks and to Marcus Island strung out northwest of it.

MIDWAY ISLANDS are sand bars of an atoll perched on one of the older peaks at the northwestern end of the Hawaiian chain of volcanoes. The atoll is centered near 177°22′ W., 28°15′ N. It is 1,182 statute miles northeast of Wake. The lagoon is from 4 to 10 feet in depth, except for a small anchorage called Welles Harbor and a small central deep lagoon with depths to 60 feet.

OAHU ISLAND is one of the cluster of volcanic islands toward the southeastern end of the great 1,500-mile Hawaiian chain. It is centered near 158° W., 21°31′ N., about 1,300 statute miles southeast of Midway. Although there are youthful cinder cones clearly visible from the air on Diamond Head and Koko Head and the entire island is built of lava flows, there is no record of modern eruptions. It is best known for its Pearl Harbor and the city of Honolulu.

By the end of World War II, air travel across the Pacific had

become almost commonplace. The main trail from Manila to California as flown by the Air Transport Command had substituted Kwajalein and Johnston islands for Wake and Midway as stops between Guam and Oahu.

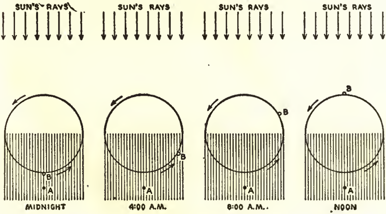


Kwajalein Atoll.

KWAJALEIN ISLAND is a small piece of dry land topping the southeastern corner of the reef of Kwajalein Atoll, one of the largest in the world. The atoll is 70 miles in its longest dimension and centered about 167° E., 9° N., among the Marshall Islands, 1,600 miles southeast of Guam. There are 90 islands strung around the crest of the atoll's coral reef. The atolls of the Marshall Islands rest on volcanoes lined up along an abyssal fissure in the earth's crust from which have poured the lavas that built a nearly continuous ridge southeastward through the Gilbert Islands, Ellice Islands, and Wallis Island to Niuafou

on the border of the Pacific basin at the edge of the Austral-asiatic continental mass.

JOHNSTON ISLAND is an amazing little sand bar in the lagoon section of a submerged coral reef at about 169°17′ W., 16°44′ N. It is 1,630 miles northeast of Kwajalein and 820 miles southwest of Oahu. In 1923 it was 3,000 feet long, 13 feet high at one end and 44 feet at the other. By 1945, its length had



Sketches to illustrate discussion of Greenwich Time and the Date Line.

been more than doubled and its maximum height reduced to 11 feet to prepare it as an air base. It is perched on a volcano that has no apparent structural affiliations with its environment, an isolated lonely pile of lava on the ocean bottom very nearly in the geographical center of the true ocean basin, which became one of the busiest airways crossroads of the Pacific.

Flying over these waters, a passenger has to master the meaning of Greenwich Time, time zones, and the international date line or he never does know when he is where or how long it took to get there. The reason for the date line usually seems to be the most elusive. One approach to an understanding can be made by visualizing a curved line in space fastened to a point

near the sun and suspended over the dark half of the earth from North Pole to South Pole. Then consider the date line immediately under this reference line at a minute after midnight Sunday morning. Anchor observer *B* (for boat) in a boat on the date line (it purposely misses all land masses) east of the Marshall Islands 10 degrees north of the equator and allow him to ride with the earth as it revolves about its axis. Seat observer A (for airborne) just above *B* in the air on our line that is tied to the sun. For him it is going to be midnight all the time because we deliberately put him on the side of the earth away from the sun and are now leaving him in space there.

Now consider conditions as the earth spins around its axis, whirling its surface from west to east. Our observer *B* is in his boat on the date line on the opposite side of the earth from the astronomical observatory at Greenwich, England, from which time is arbitrarily counted and longitude measured. He rides with the earth as it spins. Our observer A is fastened to a sky hook anchored in space while the earth spins beneath him and he watches familiar lands flash by. We can figure in advance how fast the scenes will pass beneath him. The earth is traversed from pole to pole by 360 reference lines called *meridians*, used to mark off the longitude or distance around the earth parellel to the equator. We call a *day* the time required for it to spin once on its axis, so the 360 lines pass a point in space in 24 hours. That is at the rate of 15 per hour. So we say that 15 degrees of longitude are the equivalent of one hour of time, and 15 degrees will pass under our observer A each hour.

Suppose we examine the situation one hour after the start of the experiment, when A and *B* were together at one minute after midnight Sunday morning. *B* has moved toward a position from which he will soon catch a glimpse of the sun as it appears to rise above the eastern horizon. For him it is one o'clock Sunday morning. But A, hanging in space, is now over the meridian called 165° E. and Kwajalein has just passed be-

low him. At A it is just after midnight and Sunday morning is beginning.

Let another hour pass and for *B* it is two o'clock Sunday morning. The meridian 150 degrees east of Greenwich is now under A. Truk and other Caroline islands have just passed him. There it is, as always for A, a minute after midnight Sunday morning.

If we wait a couple of hours now, we find it four o'clock Sunday morning on the date line with observer *B*. *A* is over the meridian 120 degrees east of Greenwich, not far from Manila in the Philippine Islands, where it is, accordingly, a minute after midnight Sunday morning. On the date line, *B* will before long now be seeing the heavens brighten in the east as his part of the earth swings around to where the sun appears to rise over the eastern horizon. But 4 hours will have to pass before Manila reaches that same strategic position with reference to the sun, so we speak of date-line time being 4 hours "ahead" of Manila time. In the same way, *The time at any point on the earth is "ahead" of the time at points west of it.*

Consider the situation 8 hours later. Dawn has come and the sun is high in the heavens over *B* on the date line, where it is noon Sunday. *A* is suspended over the 0° meridian, which passes through Greenwich, England, and all along which it is now a minute after midnight Sunday morning. Of course, time has also been passing at other places we've just considered. A little arithmetic will show that it is now 11:00 A.M. Sunday on Kwajalein and 8:00 A.M. Sunday at Manila, while it is 12 noon Sunday on the date line and just after midnight Sunday morning at Greenwich.

Five hours later, it is five o'clock in the afternoon Sunday for our man *B* on the date line, and our experiment has been now running for 17 hours. *A* is wearily watching scenes on the meridian 75 degrees west of Greenwich, along which it is again just after midnight Sunday morning. This applies along

the eastern coast of the United States, where so-called Eastern Standard Time is 5 hours behind the time at Greenwich and 17 hours behind the time along the western side of the date line.

Three hours later, it is eight o'clock in the evening Sunday for our man *B* on the date line, and our experiment has been running 20 hours. *A* is over the meridian 120 degrees west of Greenwich, along which it is just after midnight Sunday morning. This includes the West Coast of the United States, which is 20 hours "behind" the date-line time, 3 hours "behind" East coast time, or 8 hours "behind" Greenwich Time.

The critical part of the experiment comes as we approach midnight again. For *B*, who has been living just west of the date line, Sunday has run the full course of 24 hours and Monday is about to begin. But *A* knows that at points east of the date line Sunday has just begun. The date line could be drawn along any meridian of the globe, but once drawn, it arbitrarily establishes a point just west of it as 24 hours "ahead" of a point just east of it. Naturally, this would be slightly confusing in a populated land area. It was a convenient coincidence that a line 180 degrees from Greenwich very nearly fulfilled the desired condition of avoiding all land.

We count time from the date line, though we describe positions on the globe by using longitude lines counted from Greenwich, England. This doesn't affect any of the principles that the experiment demonstrated. With the increase of air travel, which whisks passengers through a succession of time zones at a dizzy pace, there is much to be said for setting a watch on Greenwich Civil Time (GCT), also known as Universal Time (UT), and applying corrections to determine local time at each landing field.

Simple formulas for accomplishng this are shown at the top of page 162.

$$\text{Local time} = \text{GCT} - x \text{ for West longitudes}$$
$$\text{Local time} = \text{GCT} + x \text{ for East longitudes}$$

or

$$\text{GCT} = \text{local time} + x \text{ for West longitudes}$$
$$\text{GCT} = \text{local time} - x \text{ for East longitudes}$$

where x is the number of hours representing the longitude difference between Greenwich and any place or time zone

TIME LOG OF A 1945 FLIGHT ACROSS THE PACIFIC

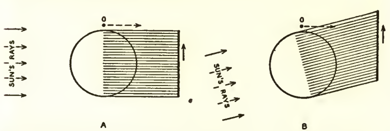
GCT	Local time	
Sunday, Aug. 12	*Sunday, Aug. 12*	
0445	1345 (1:45 P.M.)	ATC Trip 16, *The Bataan Meteor*, left Nichols Field, Manila, P.I.
1300	2300	Arrived Guam, air time 8^h15^m
	Monday, Aug. 13	
1545	0145	Left Harmon Field, Guam
2130		Passed Ujelang Atoll (10° N., 161° E.)
2345	1145	Arrived Kwajalein, air time 8^h00^m
Monday, Aug. 13		
0125	1325	Left Kwajalein
	Sunday, Aug. 12	
0930	2300	Arrived Johnston, air time 8^h05^m
	Monday, Aug. 13	
1050	0020	Left Johnston
1505	0635	Arrived Hickam Field, Oahu, air time 4^h15^m
2015	1045	Left Hickam Field
Tuesday, Aug. 14	*Tuesday, Aug. 14*	
0800	0100	Arrived Fairfield, Calif., air time 11^h45^m

under consideration, at the rate of one hour for each 15° of longitude.

For example, Eastern Standard Time is the time for 75 degrees west of Greenwich. For that time zone $x = 5$. If it is seven o'clock in the morning, or 0700 GCT, then Local Time EST = 0700 — 0500, or 0200, two o'clock in the morning. It is necessary to express time from 0000 hours for midnight through 2300 (23 hours 00 minutes) for 11:00 P.M. to use these formulas.

A detailed time log for a flight over this modern trail across the Pacific showing how the ocean had shrunk as a transportation barrier by the end of World War II is on p. 162.

A summary of the times shows 40 hours 20 minutes in the air and 10 hours 55 minutes on the ground for a total elapsed time of 51 hours 15 minutes from leaving the ground at Manila to touching at Fairfield, Calif.



The shades of night rise. Observer in plane is at O, with back to sun.

The Shades of Night Rise

A passenger leaving Oahu in the afternoon bound for the United States finds himself with twelve hours in which to ponder the mysteries of the universe and listen for irregularities in the beat of the plane's motors. From the vantage point of 9,000 feet up, also, he sees how wrong are the poets who for generations have been spinning fantasies about the shades of night falling, because he can sit there and watch them rise.

As the sun dips below the horizon behind the plane, the earth's shadow climbs out of the horizon in the east and mounts steadily into the vault of the sky against a backdrop of faint scattered light thrown back to the observer's eye by the earth's atmosphere. It is a sight majestic beyond the limits of tortured phrases of a mere earthbound poet, or an airborne scientist.

WAR-NAME ISLANDS

World War II brought into the news many other islands which are examples of the principles we've been discussing. Frequently it looks almost as though structural relationships guided military operations.

Most of the action around Australia involved islands fringing the Australasiatic continental block. The *Solomon Islands,* including *Guadalcanal* and *Bougainville;* the *Bismarck Archipelago,* including *New Britain* with its harbor of *Rabaul;* and the *Admiralty Islands,* of which the principal is *Manus,* are closely associated, with complex crustal folding and andesitic volcanoes controlling their form and distribution. Earthquakes are frequent and severe, including many of the geologically interesting deep-focus types.

Halmahera, just north of the equator 128 degrees east of Greenwich, fits into the structural picture as the hinge point where the Shichito-Marianas arc terminates and the Australasiatic continental block swings sharply eastward.

The *Palau Islands,* including *Anguar, Peleliu,* and *Babelthuap,* are in the vicinity of 134° 5′ E., 7° 5′ N. and constitute one of the southern echelon links in the Shichito-Marianas arc. They are predominantly volcanic but also characterized by recently elevated barrier reefs which are unique and have produced valuable fleet anchorage areas. Part of the "elevation" of the reefs would be due to the recent world-wide lowering of sea level, which brought most of the low-lying coral atolls into

existence in the deep Pacific, but the total is greater than this would have explained. The difference is traced to local uplift through swelling and heaving as this arcuate segment of the great continental mountain front yields to internal forces.

Guam has been mentioned as one of the stops on modern trans-Pacific airways. It is the largest of the Marianas Islands, which also include north of Guam, *Rota, Tinian*, and *Saipan*. These are not far from 15° N., 145° E. They are all peaks on the major mountain arc bordering the region of Australasiatic continental rocks. The Marianas are noted for their many flat terraces produced by wave action when land and sea stood in different relationships. Guam and Saipan have clearly-outlined extinct volcanoes.

Iwo Jima (Sulphur Island), one of the Kazan Retto (Volcano Archipelago), at 141°18′ E., 24°47′ N., became one of the most densely manned, violently contested battlefields of the world in 1945. Iwo is the most common spelling in Roman letters of the Japanese pronunciation of their character for sulphur, though an alternative is *Iō*. In pronunciation, the "w" should not be sounded, though actually it is almost universally, as approximately "ee-woe." Just for the record, though the world's mispronunciation will undoubtedly outweigh and outlive the original Japanese version, Iwo should actually be pronounced with only casual attention to the "i" and a long "o", somewhat like "ee-oh-h," while the "j" in Jima is a modification of the original "sh" in Shima for island and Jima sounds more nearly like "zhee-ma."

Iwo Jima is the central island of the Volcano Group and for that reason is sometimes called Naka Iwo Jima (Central Sulphur Island). North of it is Kita Iwo Jima (North Sulphur Island). Iwo Jima is shaped like a gourd with its neck at the southwest end and long axis running northeast-southwest. It is about 5 miles long and a little over 2 miles wide at the widest part. It and other islands of the group are the emergent tips of

a large domal swell on a submarine ridge covered by an average of 3,000 feet of water.

In a geological sense, Iwo Jima is a very young island. It was built up to and above sea level by a series of submarine eruptions from the vent now known as Suribachiyama. At about the same time, some of the lava from the depths worked its way off to one side northeast of the vent and squeezed its viscous mass between rock layers it found there. The result was an arching of the rocks above and formation of a flat-bottomed, roughly circular, dome-shaped body of igneous rock known as a *laccolith*. In the Black Hills of South Dakota, Bear Butte is the igneous core of such a mass, with its cover removed by erosion and a ring of upturned strata around its base. As the dome of Motoyama formed, it approached the surface of the sea until the water over it became shallow enough to support coral growth. By progressive intermittent stages, the doming continued until now there are above sea level a number of flat terraces which were planed by wave action. The uplift was greatest on the northeastern end of the island. At one stage of the uplift, there were two islands, Motoyama and Suribachiyama, separated by a shallow bar. Then occurred the first eruption of Suribachiyama above sea level. It blew out material which formed the present cone. Continuing uplift brought the shelf between the islands out above the sea to form the gourd's neck and the beaches on which the U.S. Marines landed. Uplift is going on at the present time at a sufficient rate to have caused several places from which it was once possible to fish and launch canoes to be now many feet inland.

There has been no eruption of Suribachiyama during recent historical time, though a submarine eruption near Minami Iwo Jima in 1906 formed a short-lived island which has now succumbed to wave action. Also, there are sulphur fumes issuing from Suribachiyama's crater and from a number of places on the Motoyama dome. The volcano cannot be regarded as extinct

and should be watched if the island is occupied permanently by any number of people. Suribachiyama is a truncated cone with a base diameter of a little over a half mile. At its summit is a funnel-shaped crater roughly circular in outline and about 1,500 feet in diameter. The highest point above the sea is 500 feet. The crater bottom is circular in outline with a diameter of about 1,000 feet and a depth of about 300 feet below the highest point of the rim. The flanks of the cone slope at about 30 degrees, in the natural form assumed by material ejected from the volcano, for only a short distance from the crest. From there downward they form almost vertical cliffs with heights varying from over 300 feet on the southwest side to 60 feet on the northeast. On the northeast side fronting the sand flats, the cliff is fringed along its base by an uplifted terrace about 60 feet above present sea level. There is no corresponding terrace on the southwest side. The vertical cliffs represent old sea cliffs cut when the sea stood some 60 feet above its present level, or the land that much lower and when the volcano was surrounded by water. After the island emerged in its present form, the terrace on the northeast was protected from further erosion by waves. Its companion terrace on the southwest side, however, was exposed to action of the sea driven by prevailing winds from the southwest and was cut away.

Okinawa is the largest land mass of the island arc known as the Ryukyu Retto (Ryukyu Archipelago) or Nansei Retto (Southwest Archipelago). In days before Japanese control they had been called the Loochoo Islands. At about 26° N., 128° E., it is near the center of the island arc curving between Kyushu and Taiwan (Formosa). This arc bounds the East China Sea on its Pacific side. The islands top a sweeping arcuate submarine ridge convex toward the Pacific. Behind or west of the land masses along this ridge is a row of volcanoes. In front, or east of the islands, is a small trough with maximum depth of 22,000 feet in contrast to a general depth between the

Ryukyus and the Shichito-Marianas arc of around 15,000 feet. The island of Okinawa is about 75 miles long and varies in width from 2 to 10 miles. The greatest elevation is 1,650 feet. The northern three-quarters is relatively rugged topographically, while the low, flat southern part is capped with coral indicating recent emergence from the sea. It lies directly in the path of some of the most violent Far Eastern typhoons.

In 1853, Commodore Perry, of the U.S. Navy, visited Okinawa and recommended establishing a United States base there. No action was taken in Washington. Japan occupied it in 1875. It was established as a United States base after military action in 1945.

Tidal Waves

Great crowds were celebrating a festival day along the coast of the Sanriku district of the Pacific coast of Japan. (San = three; riku = land or shore; Sanriku = three coastal provinces.) This embraces the prefectures of Aomori, Iwate, and Miyagi, from about 38° to 41° N. and 141° to 142° E.

The day was Monday, June 15, 1896. At seven in the evening, the long, undulating roll of earth waves from a distant quake shook the area. The tremors were not violent because of their distance from the source. They came from a great submarine earthquake in the vicinity of the Tuscarora Deep off the Sanriku coast. The people continued their merrymaking, unaware that they had been warned of impending doom. Twenty minutes later the sea quietly but ominously began to withdraw from the shore line with a speed and to a distance exceeding any ordinary low tide. Still the tempo of tragedy was slow, almost lazy. Shortly after eight o'clock, a sound from the sea was heard. It was like a sudden rainstorm. Then the water returned in a great surging sweep, piling higher and higher as it approached the shore until in places it was a wall between 75 and 100 feet high, engulfing whole villages and leaving no trace of survivors or buildings. Fishermen some distance out at sea at the time noticed nothing unusual. As they returned to port the following morning their first intimation of catastrophe came when they found the sea strewn for miles with corpses and the wreckage of buildings.

In a few brief minutes, 27,122 persons were killed and thousands injured; 10,617 houses were swept away and many others partially destroyed.

This Sanriku tidal wave was caused by a submarine earthquake. The explosion of the volcano Krakatoa on Monday, Aug. 27, 1883, as previously mentioned, set up a wave of water which swept over low-lying coasts of western Java and southern Sumatra and killed 36,500.

Wind also can drive ocean waters beyond their normal boundaries with disastrous effects. After a hurricane struck inland over Long Island and up the Connecticut River valley on the afternoon of Wednesday, Sept. 21, 1938, great waves from 30 to 40 feet high inundated sections of the New England coast, drowning hundreds and washing away entire settlements.

Tidal waves from any of these causes are particularly hazardous to some of the low-lying Pacific islands. One account, preserved by H. S. Cooper in his *Coral Lands* (London, 1880), tells us: "In May, 1877, when I was sailing in a cutter in the Fiji Group, there was a terrible wave which swept away thousands of the inhabitants of the atoll islands, some of which disappeared altogether." It has been suggested that this wave was generated off the coast of South America by an earthquake near Iquique, Peru.

THE TIDES

These tidal waves came into being under special circumstances and were of destructive proportions. There is another tidal wave which courses the oceans, twice daily in most places, under control of the sun and moon. It causes water along coast lines to rise and fall rhythmically.

Since time began, even the most casual of observers among seaside dwellers have known that the water rises and falls in a systematic manner. Long before Isaac Newton in his *Principia* in 1687 laid the basis for modern explanations of the tides, it was recognized that there was some connection between tides and the moon as well as variation with the seasons.

It has been reported that early Chinese writers suggested two causes for the tides. One, by analogy, regarded the water as the earth's blood and the tides the beating of its pulse. Another stated that tides were caused by the earth's breathing. One E. G. Browne translated a passage from the *Wonders of Creation* of Zakariyyā ibn Muhammad ibn Mahmūd al Qazvīnī, who died in 1283, as follows:

Section treating of certain wonderful conditions of the sea.

Know that at different periods of the four seasons, and on the first and last days of the months, and at certain hours of the night and day, the seas have certain conditions as to the rising of their waters and the flow and agitation thereof.

As to the rising of the waters, it is supposed that when the sun acts on them it rarefies them, and they expand and seek a place ampler than that wherein they were before, and the one part repels the other in the five directions eastwards, westwards, southwards, northwards, and upwards, and there arise at the same time various winds on the shores of the sea. This is what is said as to the cause of the rising of the waters.

As for the flow of certain seas at the time of the rising of the moon, it is supposed that at the bottom of such seas there are solid rocks and hard stones, and that when the moon rises over the surface of such a sea, its penetrating rays reach these rocks and stones which are at the bottom, and are then reflected back thence; and the waters are heated and rarefied and seek an ampler space and roll in waves towards the seashore . . . and so it continues as long as the moon shines in mid-heaven. But when she begins to decline, the boiling of the waters ceases, and the particles cool and become dense and return to their state of rest, and the currents run according to their wont. This goes on until the moon reaches the western horizon, when the flow begins again, as it did when the moon was in the eastern horizon. And this flow continues until the moon is at the middle of the sky below the horizon, when it ceases. Then when the moon comes upward, the flow begins again until she reaches the eastern horizon This is the account of the flow and ebb of the sea.

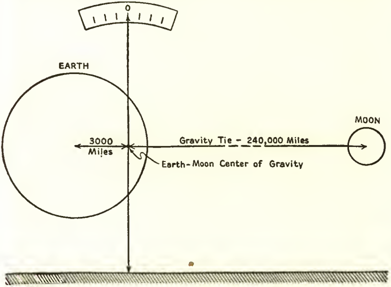
The agitation of the sea resembles the agitation of the humours of men's bodies, for verily as thou seest in the case of a sanguine or bilious man, &c., the humours stirring in his body, and then subsiding little by little; so likewise the sea has matters which rise from time to time as they gain strength, whereby it is thrown into violent commotion which subsides little by little. And this the Prophet (on whom be the blessing of God and his peace) hath expressed in a poetical manner, when he says: "Verily, the Angel, who is set over the seas, places his foot in the sea and thence comes the flow; then he raises it and thence comes the ebb."

That followed the Aristotelian scientific pattern. In the seven centuries that have elapsed since it was pronounced, many things have been learned about the tides, but the formula for explaining nature has not changed greatly: select an established fact or physical principle, if one is conveniently available (but don't let it hamper you too much if one is not); by analogy or guess, no matter how farfetched, apply it to the case in hand; polish this off with a grandiloquent phrase or two to confuse the listener or reader into thinking it should by now be entirely clear. The supernatural peroration has been losing ground.

The dominant factor in producing tides is the relationship between the earth and the moon. Certain fundamental laws are involved. One is the law of gravitation, which states that every particle in the universe attracts every other particle with a force directly proportional to the product of the masses and inversely proportional to the square of the distance between them. The other is the law of inertia, that a body in motion will continue in motion in a straight line unless acted upon by external forces. The rate of change of motion of a body is proportional to the applied force, and the change takes place in the direction in which the force acts.

An assemblage of many particles, such as the earth, behaves as though its entire mass was concentrated at one point, the

center of gravity. This is located near the earth's center. A body on the surface is thus subjected to a gravitational force directed toward the earth's center of gravity. Expressed symbolically, with M representing the earth's mass, m the body's mass, and d the distance, this is equivalent to stating that the force is proportional to Mm/d^2. If the actual force exerted on any

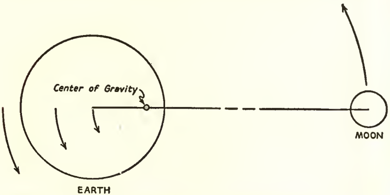


Center of gravity of the earth-moon system.

body at any distance, as, for example, the number of pounds it weighs, is divided by the value of this fraction, the same number is always obtained. This is called the universal *constant of gravitation.*

The moon, in turn, has its center of gravity. The earth and moon exert gravitational forces upon each other, acting through their respective centers of gravity, proportional to the product of their masses, and inversely proportional to the square of the distance between those centers of gravity. They

constitute a system which has its own center of gravity. If the mutual attraction between earth and moon is pictured as a rod joining their centers, a giant pin attached to this rod at the system's center of gravity could be used to balance the system on the principle of a simple lever. The system's center of gravity lies within the earth, about 3,000 miles from its center.



Earth and moon revolving about the earth-moon center of gravity.

If, for the moment, we ignore the fact that the earth is rotating on its axis once a day and consider it as a lump of matter on the short end of our gravity rod, with a mass 80 times that of the moon on the long end, we can picture the two bodies as revolving about the center-of-gravity pin once a month. This system's center of gravity at the same time revolves about the sun once a year. The gravity-rod is 240,000 miles long, or 60 times the earth's radius. The forces that result from these gyrations of the earth-moon system cause tides.

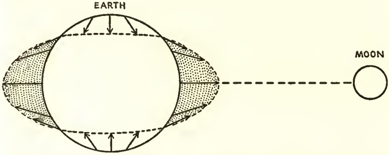
The particle at the center of the earth is in the position representing the average distance of all earth particles from the moon, that is, 60 earth radii. The average attraction of the moon for all earth-particles is therefore proportional to $1/60^2$ or $1/3600$. A point on the earth directly under the moon, how-

ever, is at a distance of 59 earth radii, while one on the opposite side of the earth is 61 earth radii. The respective lunar attractions at these distances are proportional to:

Closest to the moon	0.00028727
Average	0.00027778
Farthest from the moon	0.00026875

Closest to the moon is greater than the average by 0.00000949
Farthest from the moon is less than the average by 0.00000903

Thus, under and opposite the moon, forces are being exerted that lessen the normal pull toward the earth's center by nearly equal amounts. If we now picture these forces as fixed in space



Tidal force pattern which is fixed in space relative to the position of the moon and the earth's center, while the earth revolves and carries points on its surface into and out of each tide-producing zone once a day.

relative to the position of the moon and the earth's center, we are prepared to take the last step and allow the earth to start rotating again. This rotation does not affect the forces just described, but does control the effect observed by an earth dweller. It brings every point on the globe within the influence of each tide-force bulge once a day, thereby producing two high and two low tides per day as the ocean responds to the tide-generating forces. If the moon were always above the earth's

equator, these tides would theoretically be equal in height. Since it is not, one high tide is sometimes higher than the other.

Another way of thinking about the tide on the side opposite the moon is as due to centrifugal or away-from-the-center force produced by rotation of the earth's center about the earth-moon system's center of gravity.

In the same manner, the earth-sun system contributes tide-generating forces which are added to those of the moon to cause *spring tides* and tend to reduce the lunar ones to cause *neap tides.*

As usual, theory accounts for the general features of tides, but the actual details are dominated by other factors. The oceans are an almost insignificant film of liquid on the earth-globe. Their response to tide-generating forces is greatly influenced by the shapes and depths of ocean basins. At most ports there is a time interval between the passage of the moon overhead and the time of high water, which navigators call the "establishment of the port." The establishment of the port for many of the Atlantic coast ports of North America is approximately 12 hours, so that the direct tide expected when the moon is overhead actually arrives at nearly the time when theory predicts the indirect tide on the side of the earth away from the moon.

Tide gauges keep a continuous record of water levels at the principal ports of the world. From these records, it is possible to make a partial reconstruction of the form and speed of daily tidal waves in mid-ocean. On a map these are shown by a series of lines called *cotidal lines,* each of which joins places at which water is high at a specified time after passage of the moon overhead. It has been found that to make such maps come out even it is necessary to assume certain places in some of the ocean basins where the water is high at all times. There are three of these places in the Pacific, one in the Atlantic, and one in the

Indian Ocean, according to one man's interpretation of tide-gauge data.

From east of New Zealand in the south Pacific Ocean, the moon-generated tidal wave, unimpeded by land masses, sweeps eastward to the narrow passage between Cape Horn and the Antarctic Archipelago. Another wave traverses the south Atlantic from south to north in a relatively uniform sweep as far as the equator, and a third travels westward across the North Pacific. Elsewhere, conditions are more complicated.

That is the story of the true tidal wave. It is from 2 to 3 feet high in mid-ocean. Along the shore, the height of water depends on the form of the shore line. Heights of 10 feet are not uncommon in many harbors. The Bay of Fundy, in northeastern North America, is noted for its 40-foot tide cause by the manner in which the inlet narrows and shallows and forces the water to pile up.

There is also a tide in the solid earth, caused by the same forces. In the years 1913–15, Michelson and Gale set up an experiment on the grounds of Yerkes Observatory of the University of Chicago to measure this tide. Two pipes, each 500 feet long, were buried horizontally, one in a north-south and the other in an east-west direction. They were about half filled with water, and glass windows were sealed into each end so that changes in water level could be observed with suitable arrangements. The tide theoretically expected in the water was about .002 inch (two-thousandths of an inch). Changes were measured to one fifty-thousandth of an inch and found to be about 70 per cent of the expected value. This meant that the pipes themselves, therefore the crust in which they were buried, had yielded about as much as they would have had the material in which they were embedded been an earth-ball of steel.

Near the seashore, a load of water at high tide has been found to bend the crust a measurable amount. A simple horizontal pendulum, of the type sometimes used to record earth-

quakes, can be adjusted so that it is very sensitive to small tilts. A perceptible displacement of the pendulum's recording-light beam can be obtained from a tilt equivalent to a one-inch elevation of one end of a 1,000-mile lever. At the Harvard Seismograph Station, 25 miles inland, such an instrument shows that the solid ground is tilted by the load of water at high tide in Boston Harbor an amount about equivalent to a two-thirds-inch depression of a 100-mile lever.

Gravimeters developed for measuring the force of gravity as one of the methods of prospecting for oil have, on test runs, recorded the tidal fluctuations in that force as the earth's rotation carried the point of observation through the two tidal-force bulges.

Meteorologists have obtained evidence of a lunar tide in the atmosphere as well. This is difficult to observe because of countless conflicting and overlapping causes of pressure change, but there seems to be no reason for doubting its reality.

TSUNAMI, SEISMIC SEA WAVES, OR EARTHQUAKE TIDAL WAVES

Level changes of as many as 50 feet have been recorded in connection with fault movements causing earthquakes. When such changes, or extensive landslides, occur on the sea bottom, they may generate a large wave. Such a wave, popularly called a *tidal wave*, has been given a technical designation borrowed from the Japanese, *tsunami* (tsū-nah-mē; equal accent on all syllables; sneeze the first one).

It is well known that not all land earthquakes are accompanied by surface fault movements. Likewise, not all suboceanic shocks are accompanied by changes in the sea floor and the resulting tsunami. In fact, statistics indicate that only a very small percentage of oceanic earthquakes cause destructive tsunami. It was reported in 1861 that of 15,000 earthquakes

observed on coast lines, only 124 were accompanied by tsunami. Of 1,098 earthquakes catalogued by Perrey for the west coast of South America, only 19 were said to have been accompanied by movements of the water. These statistics undoubtedly refer to waves of magnitude sufficient to attract the attention of observers, for now that large numbers of tide gauges are recording constantly, many minor tsunami are recorded which would otherwise pass unnoticed. On any basis, however, the ratio of tsunami to subsea earthquakes is quite small.

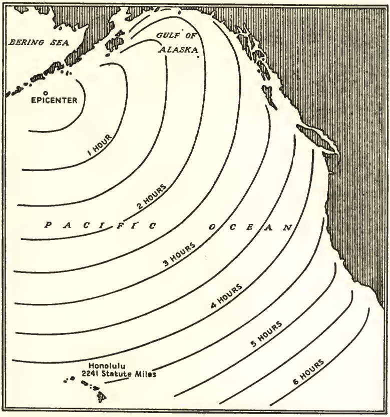
A notable feature of tsunami is that *the first motion along a shore line is a withdrawal of the water as though by an exceptionally low tide.* This is such a well-known forerunner of large waves that in places which are subject to these phenomena the inhabitants have learned to accept the warning and have time to escape toward high ground. The reactionary inrush sometimes follows the withdrawal quickly. Instances are recorded where the sea receded several miles. The time required for the water's return is variable. Sometimes it has been five or six minutes, while at others over a half hour has been required, and there are cases where the time is said to have been still longer.

The height of the returning wave depends for one thing upon the nature and depth of the bottom at any point. Over a shallow shelving bottom, or in a narrow bay, especially if it points toward the wave's source, waves may pile up to considerable heights. One of the greatest tsunami on record is one which, on Oct. 6, 1737, broke 210 feet in height on the coast of Cape Lopatka, the southern tip of Kamchatka Peninsula.

There are cases, such as at Acapulco, Mexico, on Monday, Dec. 4, 1854, when the sea is said to have returned as gently as it went out.

Tide gauges show the effects of tsunami in bays and inlets as surges, or seiches, the periods of which depend on the location and form of the bays.

The tsunami travel across the open ocean with a velocity often close to that of true tidal waves, from 300 to 500 miles per hour. At sea, they are too small to be observed. They pile



Advance of tidal wave of Monday, Apr. 1, 1946, caused by an earthquake with epicenter southeast of Unimak Island.

up to large heights only when they enter shallow water. They measure from 100 to 400 miles from crest to crest.

In Hawaii it has been possible to forecast the arrival of several tsunami from Alaskan earthquakes in particular. It is now

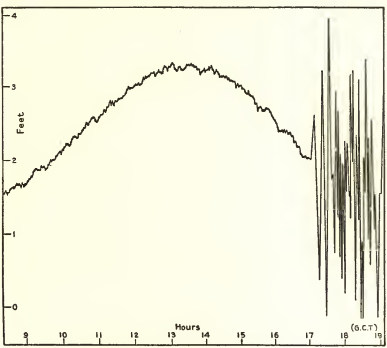
customary, when a severe earthquake is recorded which is believed from its computed distance to have been suboceanic, to issue tsunami warnings just as the Weather Bureau issues storm warnings. The transit time for *P* and *S* is minutes as compared with many hours required by the tsunami.

Of eleven tsunami, the rates of propagation reported by the Hawaiian Volcano Observatory have varied from 280 to 480 statute miles per hour. An earthquake 3,900 miles from Hilo in the Acapulco Deep off Mexico jolted coast towns there at 4:49 P.M. on Saturday, June 16, 1928. The tsunami arrived at Hilo on June 17, at 1:18 A.M., having traveled 7.7 miles per minute. The waters at Hilo rose and fell 1.3 feet. The periods of the oscillations were from 15 to 22 minutes, and the disturbed condition was recorded for more than 24 hours. The record was very feeble on the Honolulu tide gauge.

A spectacular tsunami was generated in the early morning hours of Monday, Apr. 1, 1946, at the time of a severe earthquake at 53.5° N., 163° W., about 80 miles southeast of Unimak Island, Alaska, where the ocean is about 12,000 feet deep on the steep slope of the Aleutian Trench. The earthquake occurred at about 12^h29^m Universal Time, nearly 2:00 A.M. Hawaiian Standard Time, and the records on Hawaiian seismographs were not seen in time to permit issuance of a tidal wave warning. Four hours and 34 minutes later, the tsunami reached the Honolulu tide gauge, having traveled 2,240 miles at 490 miles per hour. There the water first rose about 8 inches in 6 minutes. It then fell 2 feet in 7½ minutes. This was a general pattern for all stations. The average ratio of initial rise to succeeding fall was about 1 to 3. This suggests that the almost universal eyewitness reports, that tsunami first cause a withdrawal from the shoreline, are due to the fact that the withdrawal is more striking, but that actually the true front of the wave is a relatively small crest.

This tsunami was traced by tide-gauge records to Valparaiso,

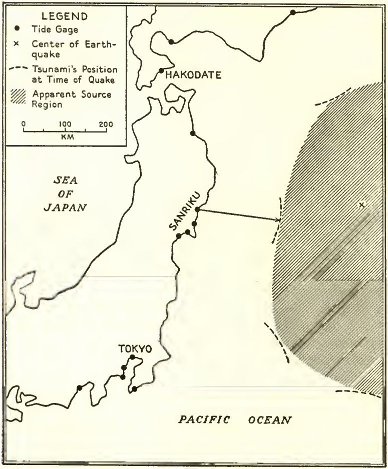
Chile, where it was still able to produce 5-foot fluctuations 8,066 miles from its source. Its average velocity to that station was 445 miles per hour. Wherever it approached a coast through shallow water, it rapidly lost energy and speed. In the



Honolulu tide gauge record of tsunami of Apr. 1, 1946.

open ocean, it apparently had a height of no more than 2 or 3 feet, and traveled as a series of crests about 100 to 125 miles apart, with about 15 minutes elapsing after one crest passed before the next arrived. Tide gauges showed tsunami disturbances for many hours. In fact, at Matarani, Peru, activity of the tsunami type was still being recorded three days later.

The Sanriku tsunami of 1896 has been described. On Friday, Mar. 3, 1933, the same coast was visited by another large



Apparent source region of Sanriku tsunami of Mar. 3, 1933. (After Miyabe)

but somewhat less destructive wave. It was the fifteenth of a series caused by earthquakes from July 13, 869, to that date. Following the 1933 event, an intensive scientific study of the phenomena was conducted, embracing field observations, the-

ory, and laboratory experiments. The results were reported in a special volume of 521 pages, many in English. This is the most exhaustive quantitative study of the subject in print.

An observer named Miyabe correlated arrival times for the 1933 wave at mareograph stations along the Japanese coast. From arrival times at the stations, he worked backwards to the apparent place of starting and found it to be an area about 400 miles long. That was about double the distance between crests of the wave which reached shore 30 minutes apart. The first wave reached Honolulu, 3,000 miles away, in 7 hours and 32 minutes; San Francisco, at a distance of 4,650 miles, in 10 hours and 22 minutes; Santa Monica, Calif., 5,035 miles away, in 10 hours and 56 minutes.

The height of the wave in the bays of the Sanriku coast depended directly on the slope of the bottom and the angular relationship between the bay's long axis and the direction to the earthquake's source.

The advancing wave exerted a pressure of 800 pounds per square foot on a wave-stroke dynamometer at one place. It was computed that to stop it suddenly in water 15 feet deep would have required a force of about 6.5 tons per square yard.

The wave height increases as depth decreases, until it becomes half the depth, at which point the wave breaks. The falling velocity from the crest then combines with the velocity of advance to develop greater pressures. It was computed that these might become as much as 49 tons per square yard for a wave 30 feet high.

Earth or concrete walls and groves of trees serve as sufficient protection from small waves, but if waves are likely to exceed 100 feet in height, the only sure protection is to build on high ground.

WORLD-WIDE CHANGES IN SEA LEVEL

The sea has many times encroached upon the land or withdrawn for long intervals from a onetime shore by mechanisms entirely different from those of tidal waves. Sea level the world around has undergone some fantastic fluctuations.

If the ocean washes for long enough against a rocky coast, it notches and cuts its way shoreward until it has planed off a wave-cut terrace. Then, if the sea withdraws to a lower level or the land is elevated by local forces, this terrace becomes a unique coastal land form preserving a record of the former relation between ocean and land. Generally, if local forces have elevated the land, there is tilting as well as change in level.

Changes in level of water at the shore line affect the flow of rivers also. With rising sea level, rivers which had been at work reducing the land to the level of the water find themselves with less to do. Many which have temporarily overshot their goal are then able to build gravel terraces along their courses, and these become evidence of the higher shore line.

In 1840 Louis Agassiz' book on the ice age first established the idea of continental glaciation. Two years later, Maclaren in a review of the book (*American Journal of Science*, Vol. 42, p. 346, 1842) asked the question, "What effects have glaciation and deglaciation had on ocean level?" Answers were slow coming in. At an accelerating rate in recent years, however, observations have accumulated until there is no doubt that world-wide or eustatic shifts in sea level have occurred many times in the past. It appears, further, that some of them were too great to be explained as effects of glaciations.

Scattered around the world are sets of wave-cut terraces, some below present wave base and others above present sea level. They tell a startling story about fluctuations in sea level on a world-wide scale because many of them are at so nearly the same elevation in widely scattered places that they could

not have been produced simultaneously by independent forces acting locally, and the changes must have been in the ocean itself.

The problem of making comparisons of shore lines on a world-wide scale is complicated by a number of factors. As one example, if sea level is lowered by withdrawal of water to form great sheets of ice on certain land areas, the effects of that ice load in distorting the solid earth make the relations between land and water something less than simple. Readjustments in the solid earth likewise enter the picture when the process is reversed and water returns to the oceans as the ice sheets melt.

Coral formations are particularly useful recorders of previous sea level because they do not develop high above the sea or in depths much greater than 100 feet. Accordingly, if one is found at 1,200 feet above present sea level, it is a significant thing. Such a formation has been described on Espiritu Santo Island (about 17° S., 167° E.) in the New Hebrides group, 500 miles from Guadalcanal, and one of the supporting air bases for the invasion of the Solomons, Friday, Aug. 7, 1942. It corresponds to a 1,200-foot terrace in the Hawaiian Islands 3,000 miles away. One investigator who has made a special study of this problem has tabulated some shore lines of the past couple of million years. Many of his data came from such scattered places as the Hawaiian Islands, the Marianas, the Solomons, the New Hebrides, and the Atlantic coast of North America. Two Japanese investigators have analyzed detailed sea-bottom contour maps and described nine submerged terrace levels.

ALTITUDES OF PAST SHORE LINES

(Referred to present sea level, measurements in feet)

Espiritu Santo Island [1]	Hawaiian Islands [1]	U.S. Atlantic Coast [1]	Japan-Korea [2]	Truncated suboceanic peaks in Pacific [3]
+1200	+1200			
+560	+560			
+260	+250	+270		
+215		+215		
+100	+100	+100		
	+70	+70		
+45	+40	+42	+45	
+27	+27	+27		
+5	+5	+5		
Sea----------	----------	----------	----------	----------Level
			−10	
			−45	
−60	−60			
			−75	
			−150	
			−270	
−300	−300			
			−390	
			−645	
			−975	
	−1200			
				−1500
			−2100	−1800
				−2400
				−4500

[1] Data from H. T. Stearns, *Bulletin* Geological Society, 1945

[2] Data from Yabe and Toyama, *Bulletin* Earthquake Research Institute, 1934

[3] Data from Murray and Hess, *Transactions* Amer. Geophys. Union, 1946

CHAPTER 7

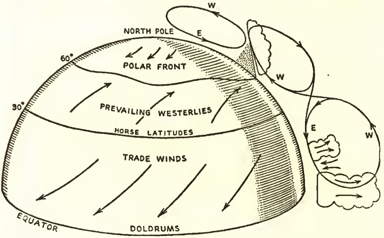
Hurricanes and Typhoons

The earth's atmosphere joins its solid body and watery surface veneer as another medium through which violent forces and catastrophe are thrust upon us in our struggle for existence on the restless globe.

The atmosphere near the earth's surface, where it is of most immediate interest to us, is a mixture of approximately 78 per cent nitrogen and 21 per cent oxygen with the remaining 1 per cent distributed among argon, carbon dioxide, hydrogen, and the rare gases. This composition is essentially constant to a height of 12 miles. This turbulent ocean of air reacts strongly to differential heating of polar and equatorial zones by the sun, and its behavior at the surface is notably influenced by the earth's rotation.

There is an underlying pattern of circulation that the air tries to maintain. Details differ with the seasons and the part of the globe. In a general way, however, intensely heated air in the equatorial regions rises and moves away from the equator. In the Northern Hemisphere, this air also moves from a westerly direction toward the east at height. At about 30 degrees from the equator, it has cooled enough to start a downward course, and this piles it up at the surface to create a region of high pressure. From these subtropical high-pressure areas, air moves toward the equator, gradually picking up speed until it becomes the "trade winds," or steady winds from the northeast. It also moves toward the pole, gradually picking up speed until it becomes the prevailing southwesterly wind of the temperate zone. In latitudes around 30 degrees this results

in a relatively calm belt with little or no surface wind most of the time. These are known as the *horse latitudes.* One story accounts for this name as originating from the fact that a British explorer named Ross described the conditions so effectively that German maps began to appear with the designation

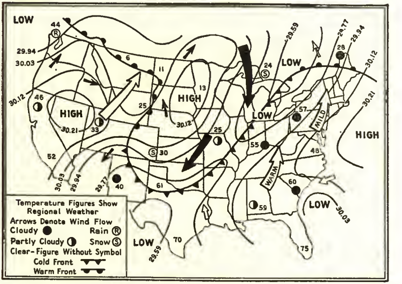


Basic pattern of atmospheric circulation in northern hemisphere. Vertical movements are shown at the right. Air rises over the equator, forming cumulus clouds, moves northward and from the west (indicated by the "W"), then descends in the horse latitudes, to sweep over the surface southward and from the east as the trade winds. (After C. G. Rossby, in United States Department of Agriculture Yearbook, *1941*)

"Ross Breiten" or "Ross Latitudes" in the 25-35-degree region. English-speaking users of these maps then interpreted them with the aid of a dictionary instead of a history book and, since "Ross" in German means "horse," started calling them the horse latitudes.

Air over the poles soon becomes relatively chilled, shrunken and dehydrated. It tends to flow down over the globe with a swirl that produces strong easterly winds in the Northern Hemisphere and westerly winds in the Southern by the time it

reaches about 60-degree latitude. There the polar air masses are in perpetual conflict with warmer air masses moving across the surface in the opposite direction. These masses wage their battles over the Temperate Zone and the results dominate the weather on those battlefields. Giant undulations course along

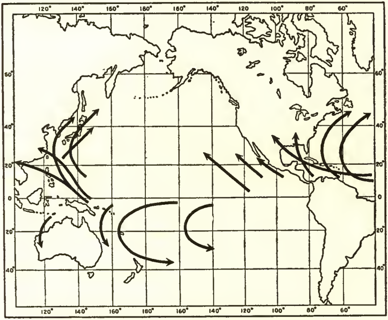


Weather map of United States, showing zone of conflict between polar and tropical air masses. A tongue of cold air has penetrated the battle line as far as northern Texas, while one of warm air has counter-attacked as far north as Maine, along the east coast. Near the point of flexure in the front, a low-pressure storm center is developing.

the polar front as tongues of polar air penetrate the tropical lines, and the reverse. The polar air advances along a cold front and the tropical along a warm front. The advances are never in straight courses. In the Northern Hemisphere, both tongues tend to develop a counterclockwise whirl. As this takes form, the embattled masses twist in a local eddy around a low-pressure area. Chilling of moist tropical air causes precipitation

and a storm is born. This drifts across the battlefield on the current of the prevailing winds, as what is called an *extratropical cyclone*. In the Southern Hemisphere, the cyclonic circulation is clockwise.

Quite different in origin and character is another type of storm known as the *tropical hurricane*. In regions bordering



Normal tracks of typhoons and West Indian hurricanes.

the Atlantic Ocean such storms are often known as *West Indian hurricanes*, while in the Pacific they are called *typhoons*. Meteorologically and humanistically, they are the same thing.

Tropical hurricanes occur over the north and south Pacific Ocean and the Bay of Bengal. The name is derived from the fact that they originate in the tropics. Once started, they may travel far north. Many in the north Atlantic have been charted as far as Iceland.

A tropical hurricane is essentially a vortex, or narrow, nearly circular region of calm surrounded by twisting currents of air rising rapidly in a manner the reverse of that in which water will often escape from a basin when a stopper is removed from a small drain. It originates in the doldrums, or calm regions of tropical oceans, and is maintained by inward-flowing, warm, humid air which replaces the rising column and whirls around the center in a counterclockwise direction north of the equator and a clockwise direction south of the equator.

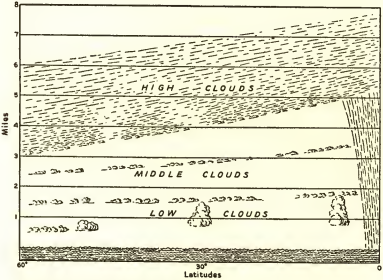
The West Indian hurricane's place of origin depends to a great extent upon the season of the year. Between 1886 and 1924 the U.S. Weather Bureau found no evidence that any started closer to the equator than 9 degrees. During August and part of September, conditions favorable to the formation of a hurricane seem to occur most frequently just south of the Cape Verde Islands (10° N., 20°–25° W.). One investigator found they never develop over the two-thirds of the Caribbean Sea east of longitude 78° W.

Far Eastern typhoons seem to find a happy breeding ground in the vicinity of the Caroline Islands and Marshall Islands, though our best records of storms that have been studied do not usually begin until they have reached or passed the Marianas Islands.

West Indian hurricanes form and run their courses at the rate of anywhere from a couple to a dozen a year. From 1887 through 1923, 33 per cent occurred in September, 30 per cent in October, and 16 per cent in August, with occasional others scattered through May, June, July, November, and December. In August, 1893, there were four in progress simultaneously from the sixteenth through the twenty-sixth. One of these pursued a path inland across New York City on Thursday, Aug. 24, and another struck inland near Savannah, Ga., on Monday, the twenty-eighth, ran parallel to the coast with its

center just west of New York City on the twenty-ninth, crossed the Gulf of St. Lawrence on the thirtieth, and finally worn itself out off the coast of Norway on Sept. 7.

Three hurricanes and a severe storm were in simultaneous progress from Sept. 9 through Sept. 16, 1900. One of these, known as the Galveston hurricane, struck that city on the afternoon of Saturday, Sept. 8.



Heights of clouds at different latitudes. (After C. F. Brooks)

The service of ocean swells which outrun the storm as advance warning of an approaching hurricane in the Gulf of Mexico has been described. The late Reverend Beniot Viñes, S.J., director of the Belen College Observatory, Havana, Cuba, discovered certain laws governing the movements of high clouds which may be used to help in determining both the existence and the position of an approaching hurricane. He summarized his observations in the form of a general law:

In the West Indian cyclones the rotation and the cyclonic circulation take place in such a manner that the inferior currents, as a rule, converge more or less toward the vortex; at a certain altitude the currents follow a nearly circular course, and higher still their course is divergent. It is particularly to be noticed that this divergence is all the greater as the currents occupy higher altitudes, until a point is reached where the highest cirrus clouds are seen to move in a completely divergent radial direction.

Cirrus is the name designed to fibrous, wispy white clouds which form at heights of 6 to 8 miles. They are tendrils of ice crystals condensed from a meager supply of moisture carried into the stratosphere by convection currents and serve as tracer bullets to mark the course of those currents. As they thicken and merge into a nearly continuous cloud, though still of the fibrous texture, they are known as *cirro-stratus,* which are usually at lower levels.

According to the observations of Father Viñes, at a place on the ground north of the vortex of a hurricane, the wind will be from a little north of east, and low-level clouds will move from the east. *Alto-cumulus,* the detached fleecy clouds with shaded portions, often in closely packed groups and rows, at heights of about 2½ miles, will move from the east-southeast. Cirro-stratus, the next highest, will move from the southeast, and the thinnest and highest cirrus clouds will move from due south as radial convection currents at the top of their orbit.

During a hurricane from Sept. 7 to Sept. 14, 1919, the United States Weather Bureau charted upper-air wind direction by means of pilot balloons and found them to conform to the expected directions. In that case, the winds in the right front sector at elevations of between 2 and 3 miles were in the direction of the hurricane's advance.

The true vortical form of the hurricane has been further confirmed by the observation of a region of complete calm in the center of the storm. One of the severest hurricanes that the

Gulf of Mexico has experienced originated near the Cape Verde Islands about Thursday, Aug. 5, 1915. It traveled westward, entered the Caribbean on Tuesday, the 10th, passed the western tip of Cuba at 2:00 P.M. on Saturday the 14th, and reached the coast at Velasco, Tex., about 40 miles southwest of Galveston at 1:00 A.M. on Tuesday, Aug. 17. At a point 5 miles northeast of Sandy Point there was a calm lasting 20 minutes. The storm was advancing at about 15 miles per hour, so the diameter of the vortex was 5 miles. The influence of the storm on the barometer at Houston began when the center was nearly 400 miles distant, and an area of about 540 miles diameter came within the influence of the storm as it advanced.

A hurricane which crossed the island of Puerto Rico on Wednesday, Sept. 13, 1876, had a vortex nearly 10 miles in diameter, in which there was calm for 20 to 30 minutes. The outer diameter of the storm at that place was computed as approximately 500 miles.

A report of Captain Sullivan of the American steamship *Jean* described his observations on that ship Monday, Oct. 17, 1910, in the Straits of Florida:

Ship hove to. The storm lasted from 5 A.M. to 8 P.M., during which the ship drifted against unusually strong stream from Gulf 60 miles in a direction west-southwest by west ½ west. During this time it was impossible to see the sea on account of the rain and spray. Immense seas came over the ship, even wetting down the chart house on the bridge deck, so that water had to be constantly bailed out. . . . At 11:25 P.M. the ship arrived at the center of the storm. Overhead the sky was perfectly clear, but the horizon was dirty, wind almost calm, and sea fearfully choppy. At 1 P.M. the wind came fiercely from the west-northwest of hurricane force, lasting until 7:30 P.M., when it began to moderate. . . . The barometer at the time of reaching the center at 11:25 P.M. was below the scale, but was carefully marked with the set hand, and subse-

quently with a file. This was, corrected, 27.80 inches. The barometer rose slightly on entering the center.

At Tarpon Springs, Fla., about 20 miles northwest of Tampa, the hurricane of Tuesday, Oct. 25, 1921, caused winds of 80 to 100 miles per hour before 2:15 P.M., at which time the center of the storm reached there. There was a dead calm for nearly an hour.

At Negril Point Lighthouse, western Jamaica, winds from a hurricane had attained a velocity of 80 miles per hour from the southeast at 10:00 P.M. on Sunday, Nov. 17, 1912. This continued until 2:00 A.M., Nov. 18, when the wind backed to northeast and rapidly increased in intensity until it was blowing 120 miles per hour when the anemometer was disabled. The velocity increased beyond that point, but no estimates of its maximum were made. The lowest barometer reading occurred at 6:00 A.M., and there was a lull in the wind between 5:15 and 8:00 A.M. At 9:30 A.M. the wind shifted to northwest and increased to hurricane force once more.

DIRECTION OF TRAVEL

Average expectable tracks of West Indian hurricanes depend upon the month in which they occur. During August, September, and October they tend to start westward across the Atlantic, swing northwestward, then recurve in higher latitudes into a northeastward path.

The dominant factor controlling the direction of travel is the location of high-pressure areas in the vicinity. A hurricane will start moving northward at the first opportunity, but Mitchell of the United States Weather Bureau stated in 1924 the general rule that "*any tropical storm will recurve into a trough of relatively low pressure that may exist when the tropical storm arrives in a given region, irrespective of the longitude or the time of the year.*" Any tendency for these storms to follow

certain similar tracks at a particular time of year actually traces to the seasonal distribution of high- and low-pressure areas.

SPEED OF TRAVEL

West Indian hurricanes may move as little as 100 miles per day in low latitudes near their places of formation. As they take form and work northward and westward, they tend to speed up to from 300 to 500 miles per day. After recurving and moving into middle and north latitudes, they have been known to travel 1,000 miles in 24 hours. On Tuesday, Sept. 20, 1938, a storm reached a point 300 miles east of Florida, where it was traveling northward about 17 miles per hour. The next morning it was 75 miles east of Cape Hatteras after advancing 375 miles during the previous 12 hours, for an average of about 31 miles per hour. From 7:30 A.M to 7:30 P.M., Sept. 21, it traveled 600 miles for an average of 50 miles per hour. The center was advancing at about 60 miles per hour when it struck inland near New Haven, Conn., at 3:40 P.M. EST.

WIND VELOCITIES

Winds blowing 60 miles per hour or more are defined as of hurricane intensity. In many hurricanes they do not exceed 100 miles per hour. The highest wind velocity recorded on the coast of the Gulf of Mexico was 140 miles per hour at 3:45 P.M., Wednesday, Sept. 29, 1915, at Burrwood, La., near the mouth of the Mississippi River.

Instruments for measuring and recording wind velocities are usually essentially wind-driven speedometers which record mileage only. These are reduced to miles and written records show the length of time required to accumulate a certain number of miles, say 50. This obviously averages gusts and lulls, so it is generally impossible to set a very precise figure on the

maximum in brief gusts. Another difficulty with such devices is that they often blow down just as things become interesting.

On Wednesday, Sept. 21, 1938, one vane of a windmill anemometer at Harvard University's Blue Hill Observatory, just outside Boston, flew away at the first great gust; soon the rest were torn off. The tail remained for three hours but finally took off for parts unknown in a gust of over 150 miles per hour, which also blew in an observatory window. Another anemometer held together and recorded the maximum average velocity of 187 miles per hour for one 5-minute interval. On Mt. Wachusett, just north of Worcester, Mass., the average velocity between 4:00 and 6:00 P.M., EST, on this same day was 104 miles per hour. With such high average figures, it is probable that momentary gusts reached or even exceeded 200 miles per hour.

THE DANGEROUS SEMICIRCLE

The winds about a hurricane or typhoon in the Northern Hemisphere are counterclockwise in direction. This causes those on the eastern side of a northbound vortex to be blowing in or near the direction of the storm's travel. As a result, the vortical velocity of the wind is added to the velocity of the storm's travel forward. On the west side, the velocity observed on the earth's surface is what is left after subtracting the velocity of the storm's forward travel from the speed of the winds about the vortex. If the winds twist around a vortex at 100 miles per hour and that vortex is traveling over the surface of the ground at the rate of 50 miles per hour northward, places on the east side experience a 150-mile wind, and those on the west a 50-mile wind in the opposite direction. For that reason, the semicircle of a storm on the right of an observer at its center facing in the direction of its travel is known to mariners as the "dangerous semicircle."

WIND-DRIVEN TIDES

Wind is capable of piling water to destructive heights along a coast if it blows hard enough and long enough from one direction. Effects may be particularly disastrous if the peak of the blow coincides with normal high tide.

West Indian hurricanes announce their entrance into the Gulf of Mexico and their approximate direction of travel by great swells which outrun the storms and by piling up of the water on the coast ahead of them beginning about 12 hours after the storm enters the gulf.

A story by Lafcadio Hearn, *The Legend of l'Isle Dernière*, recounts the destruction of Last Island, site of a populous resort colony off the coast of Louisiana not far from New Orleans, in August, 1856. July 31 was a calm, beautiful tropical day on the island. Then at noon,

> . . . when the blue abyss of day seemed to yawn over the world more deeply than ever before, a sudden change touched the quicksilver smoothness of the waters—the swaying shadow of vast motion. First the whole sea-circle appeared to rise up bodily at the sky; the horizon-curve lifted to a straight line; the line darkened and approached—, a monstrous wrinkle, an immeasurable fold of green water, moving swift as a cloud-shadow pursued by sunlight. But it had looked formidable only by startling contrast with the previous placidity of the open; it was scarcely two feet high;—it curled slowly as it neared the beach, and combed itself out in sheets of wooly foam with a low, rich roll of whispered thunder. Swift in pursuit another followed—a third—a feebler fourth; then the sun only swayed a little, and stilled again. Minutes passed, and the immeasurable heaving recommenced—one, two, three, four . . . seven long swells this time;—and the Gulf smoothed itself once more. Irregularly the phenomenon continued to repeat itself, each time with heavier billowing and briefer intervals of quiet—until at last the whole sea grew restless and shifted color and flickered green;—the swells became shorter and changed form. Then from

horizon to shore ran one uninterrupted heaving—one vast green swarming of snaky shapes, rolling in to hiss and flatten upon the sand. Yet no single cirrus-speck revealed itself through all the violet heights; there was no wind!—you might have fancied the sea had been upheaved from beneath. . . .

The surf continued to increase. Toward evening a cloud bank gathered over the gulf and during the night of July 31 the wind began to blow, from the northeast. A hurricane had entered the gulf from the south and passed over Yucatan sometime during July 30. Weather records were not being kept at that time as they are now, but the cause can be reconstructed from the effects. The Weather Bureau has found:

Waves and swells of greatest size and length are developed in the rear right-hand quadrant of the cyclonic area and move through the smaller waves in the front of the storm and are carried by inertia to the shore in the direction in which the cyclonic area was advancing at the time. The waves sent out in other directions, being smaller and shorter, do not persist long after leaving the cyclonic area and soon flatten out and disappear. The transference of water with the long waves and swells causes rises in the water along the coast, which increase as the storm approaches.

The rise in the water on the coast in front of the line of advance of the cyclonic area begins from 12 to 24 hours after the hurricane enters the Gulf of Mexico and indicates that the waves travel with a speed of from 30 to 45 miles per hour.

The rise in water along the shore occurs before barometric pressure or other signs give any indication of the approaching storm. The daily tides are not obscured by this rise, but the intensity and speed of travel of the storm are indicated by the rapidity of the rise. The highest water occurs a few miles to the right and at about the time of passage of the storm's center. It may affect from 100 to 200 miles of coast in that direction but does not extend far to the left of the central area of the storm.

At Last Island, on Friday, Aug. 1, 1856, "The breeze still came cool and clear from the northeast. The waves were running now at a sharp angle to the shore." This is interpreted as evidence that the storm changed the direction of its advance after entering the Gulf. It probably veered westward and remained nearly stationary for a few days. "A week later seabathing had become perilous; colossal breakers were herding in, like moving leviathan-backs, twice the height of a man. Still the gale grew, and the billowing waxed mightier, and faster and faster overhead flew the tatters of torn cloud." On the night of Sunday, Aug. 10, the storm moved in off the gulf, and Last Island, on its fatal right flank, was destroyed. The wind veered

> . . . from northeast to east, from east to southeast, from southeast to south; then from the south he came, whirling the Sea in his arms. . . . So the hurricane passed, tearing off the heads of the prodigious waves, to hurl them a hundred feet in air, heaping up the ocean against the land, upturning the woods. Bays and passes were swollen to abysses; rivers regorged; the sea-marshes were changed to raging wastes of water. Before New Orleans the flood of the mile-broad Mississippi rose six feet above highest water-mark. One hundred and ten miles away, Donaldsonville trembled at the towering tide of the Lafourche. . . . And over roaring Kaimbuck Pass, over the agony of Caillou Bay, the billowing tide rushed unresisted from the gulf, tearing and swallowing the land in its course, ploughing out deep-sea channels where sleek herds had been grazing but a few hours before—rending islands in twain—and ever bearing with it, through the night, enormous vortex of wreck and vast wan drift of corpses. . . .

Thirty years later, on the morning of Friday, Aug. 20, 1886, Indianola Beach, Tex., a bustling city of 10,000 on Matagorda Bay, was wiped off the map by a hurricane-driven tide. There had been the usual warning signs of the storm's approach, but they weren't so well understood then as now. Early in 1941, the 211th Coast Artillery of Massachusetts moved onto the site of

the ghost town for a month of firing practice with antiaircraft guns. It was to be followed by other crews from New Hampshire, Missouri, Kentucky, Louisiana, and Mississippi. It is when men thus reoccupy places once destroyed by natural catastrophe that they most need to be posted on the history and habits of the region.

THE HURRICANE OF SEPT. 18–21, 1938; OR, THE NEW ENGLAND HURRICANE OF 1938

Storms of this kind are not rare things in northern latitudes, such as New England. Tropical disturbances of varying intensities passed over some part of New England 23 times during the 37 years from 1887 through 1923. Since the seventeenth century, there have been from five to ten true hurricanes to a century in New England, and one that is especially intense and widespread each century and a half. Those are the averages of past experience; there is nothing in them to argue the impossibility of two in successive years.

By an accidental combination of circumstances, at 10:00 A.M. on Saturday, Sept. 23, 1815, a tropical hurricane turned northward across Long Island and up the Connecticut valley, spreading terrific destruction; 123 years later, a similar set of conditions lay before a northward advancing hurricane.

The United States Weather Bureau's *Daily Weather Map* for 7:30 A.M, EST, Sunday, Sept. 18, 1938, carried the following notice:

TROPICAL DISTURBANCE: The following was issued at 10:30 o'clock this morning from the forecast center at Jacksonville, Florida: "Advisory. . . . The tropical disturbance, probably of full hurricane intensity, is centered at 7.00 A.M. EST in approximately latitude 22°38′ north and longitude 62° west, apparently moving west or west-northwestward about 15 to 20 miles per hour. Caution is advised all vessels in the path of this dangerous storm."

Every port along the gulf awaited further announcements anxiously. Weather over the interior of the continent was fair, under control of a high-pressure area of considerable extent. Air traffic proceeded under cloudless skies. An eastbound transcontinental plane leaving Dallas, Tex., in the early morning of Monday, Sept. 19, was warned of uncertain conditions near the coast. It landed briefly at Nashville, Tenn., with skies clearing in the wake of a shower. At Washington, D. C., it was grounded by rain and unsettled conditions which prevailed along the entire Atlantic coast.

At 9:30 A.M. EST, Monday, Sept. 19, Jacksonville, Florida, issued the following:

> Advisory . . . Northeast storm warnings ordered 9:30 A.M. from Jacksonville to Key West, Florida. The hurricane was centered at 7.00 A.M. EST, in approximately latitude 23°45′ North and longitude 70°30′ West, which is about 650 miles east-southeast of Miami, apparently still moving west-northwestward at least 20 miles per hour. The winds will increase in the Bahamas throughout the day, reaching hurricane force during the afternoon in outlying islands and if present direction and rate of movement are maintained, the storm will reach the southeast Florida coast Tuesday morning with winds commencing to increase tonight. The Florida east coast is in the danger zone of this storm and all interests are urged to stand by for possible hurricane warnings during the day.

This meant that the Florida east coast would have been in the dangerous semicircle if the storm's course that morning had been maintained.

The high pressure persisted over the middle of the continent, however, and forced the storm to swing northward, leaving Florida relieved and unharmed. At the same time, a high-pressure area fated to play a leading part in the drama had held sway over the entire North Atlantic Ocean since Thursday, Sept. 15, and showed no signs of losing its grip.

At 9:30 A.M. EST, Tuesday, Sept. 20, the Jacksonville forecast center issued the following:

> Advisory . . . Northeast storm warnings were ordered at 9:30 A.M. EST, on the North Carolina coast between Wilmington and Cape Hatteras. The hurricane, which is of great intensity, was central at 7:00 A.M. EST, near latitude 28° North and longitude 75° West, which is about 300 miles east of Vero Beach, Florida, and it is now moving north-northwestward with the center passing some distance east of Cape Hatteras tonight, and it will cause increasing northerly winds on the North Atlantic coast, becoming fresh to strong and probably reaching gale force at exposed places on the cape, with hurricane winds some distance off shore. Caution advised all vessels in path, and all small craft from the Virginia Capes to Charleston should remain in harbor until the storm passes. The lowest barometric pressure reported during the night was 27.90 inches.

At 7:30 A.M. EST, Wednesday, Sept. 21, 1938, the storm was central about 75 miles east of Cape Hatteras moving rapidly northward. A great ridge of high pressure flanked it on the west and another on the east. Both of these ridges had been developing for days and were in complete command of the situation. Between them lay a long trough of lower pressure, with its central axis running along the Connecticut River valley. In that zone lay a great mass of warm, moist air for the hurricane to feed upon. "*Any tropical storm will recurve into a trough of relatively low pressure that may exist when the tropical storm arrives in the same region, irrespective of the longitude or the time of the year.*"

Mariners had heeded the warnings, and there were no ships in the path of the storm, so landsmen to the north could be given no warning, as they had in Florida. At 9:00 A.M., EST, northeast storm warnings were ordered north of Atlantic City, N. J., and south of Block Island, R. I., and southeast storm warnings from Block Island to Eastport, Me. These were ac-

companied by prediction of "northeast or north gales backing to northwest south of Block Island to Hatteras and southeast or east gales Block Island to Eastport becoming northwest tonight or Thursday morning."

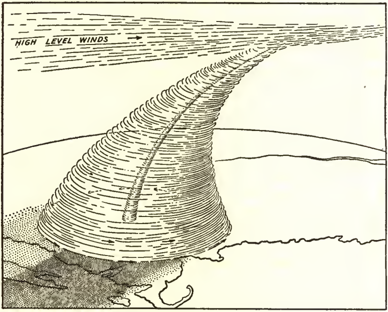
Then came: "Advisory 11:30 A.M. EST. Warnings changed to whole gale (55–75 miles per hour) Atlantic coast north of Virginia Capes to Sandy Hook, New Jersey. Tropical storm central 10.00 A.M. about 100 miles east of Virginia Capes movingly rapidly northward or slightly east of north." The ominous swing away from the customary northeasterly course was established by now, its significance clear to the experts, but landsmen were still unwarned. This notice was received at Providence, R. I., at 12:50 P.M., EST.

Finally, at 2:00 P.M., EST, there was issued an "Advisory . . . Warnings changed to northwest from Virginia Capes to Sandy Hook, New Jersey." The center had already passed, and they were getting gales from the left rear sector. "Tropical storm central 12 noon about 75 miles east southeast of Atlantic City moving rapidly north-northeastward with no material change in intensity since morning. Storm center will likely pass over Long Island and Connecticut late this afternoon or early tonight attended by shifting gales." This was received at Providence at 2:40 P.M, when the southeast gales of the right front sector of the dangerous semicircle were already howling through the streets.

Thus the hurricane swung inland over an unwarned countryside, following the low-pressure trough, and brought to New England a catastrophe unequaled in her history.

The center passed over the south shore of Long Island at 2:45 P.M., EST. (Many places in the storm zone were on Daylight Saving Time, one hour faster than Standard.) Everything on the exposed beaches was swept away. Waves accompanied it and a great cone of water swept up the shore to heights of 30 and 40 feet. Of 150 buildings in West Hampton Beach, 6

were left standing. People drowned by the scores. The vortex passed between Babylon and Patchogue. On its left flank over the western end of Long Island, the gales came from the north and northeast. From Huntington to Manhasset Bay on the



Vortex of the New England hurricane of 1938 as the eye passed across Connecticut.

north shore, blasts from Long Island Sound crushed the water front, while on the south shore, buildings at Jones Beach were blown toward the ocean.

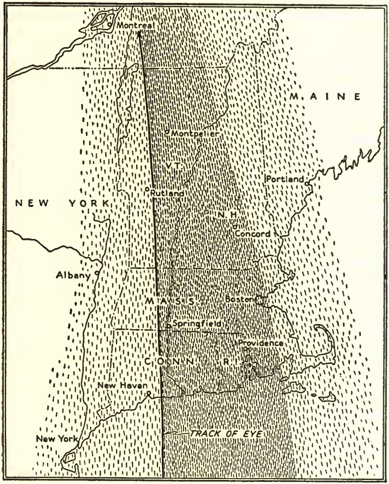
The storm center passed inland at New Haven at 3:40 P.M., EST, and northward along the Connecticut River valley. Rhode Island took the brunt of winds in the dangerous semicircle. Exposed to the unbroken sweep of the storm tide riding a scheduled spring tide, the waters of Narragansett Bay piled to record heights. Downtown streets of Providence were sub-

merged to depths that completely covered streetcars and automobiles. According to the American Red Cross, in Rhode Island alone there were 494 killed, 208 injured, 936 houses destroyed, 8,019 damaged, 3,564 other buildings destroyed and 7,120 damaged, 2,605 boats were destroyed and 3,369 damaged. Trees were destroyed in such numbers that a count was impossible. At the height of the storm, an irate lady telephoned the Providence *Journal* to complain that a tree was down on her property and the forestry department wouldn't do anything about it. Lighting, communication, and transportation were paralyzed for days and in some cases weeks. Rivers swollen by days of rain added floods to the confusion.

An hour later, an edge of the vortex brought to the vicinity of Springfield, Mass., a partial clearing of the sky and an easing of the wind, followed by an abrupt shift to the southwest and an increase in intensity.

From there it swung northwestward and by the morning of Sept. 22 had worn itself down to an ordinary low-pressure area north of Ottawa, Canada.

On the east flank of the dangerous semicircle, shortly after noon on Sept. 21, the barometers of Harvard University's Blue Hill Observatory started a downward dip that bottomed on 29.0 inches (corrected to sea level) between 5:00 and 6:00 P.M., EST, and had swung back up to the starting point by midnight. Wind velocities at noon were about 30 miles per hour. They zigzagged about an increasing average which passed 50 miles per hour at about 3:00 P.M. and suddenly at 3:15 shot to 80 at the onset of a series of wild gusts separated by "lulls" of 50 miles per hour velocities. These were from the southeast. After 5:00 P.M., the direction slowly swung more southerly, and the maximum effect of the right-limb winds blowing parallel to the direction of the storm's advance was felt from 5:00 to 6:00 P.M., EST, during which time the wildest bursts of the gale were recorded. This was when the one mentioned above aver-



Zone of greatest damage (heaviest shading) in the dangerous semicircle of the New England hurricane of 1938.

aged 187 miles per hour for five minutes. At 6:15 the velocity dropped off suddenly, and after 8:30 the violent gusts subsided and a strong blow from the southwest set in with average ve-

locities about 50 miles per hour, gradually decreasing until they reached the starting point of 30 miles per hour at about midnight.

The calm center, or "eye," of the hurricane was 40 miles in diameter over Long Island. As it passed Brentwood, for 50 minutes there was a period of calm reported "without enough wind to blow out a match." The friction of wind blowing over the ground combined with the rough topography of central Connecticut to reduce the velocity of whirl and deflect winds toward the center until the sunny eye's diameter was only about 15 miles as its eastern edge passed Hartford, and the vortex was rapidly "filling up."

On the left-hand, or west, side of the vortex, the storm's rate of forward travel was subtracted from the whirling winds' velocity and no great damage was done. Extreme velocities on skyscrapers ranged from 90 miles per hour on some to gusts of 120 miles per hour on the Empire State Building (1,248 feet high). In the Bronx, the maximum was 78 miles per hour; in Central Park, 60.

A postscript was written to the story of the 1938 hurricane over New England when a French meteorologist, Henry Hubert, traced the storm to its ultimate origin—a low-pressure area over the Bilma oasis in the south-central portion of the Sahara Desert on Sept. 4, 1938. This low moved slightly south of west to the coast of Africa near Cape Verde, which it reached on the 8th. There it received chilly northeast trade winds on one side and warm humid southwest monsoons on the other in a perfect combination for setting up cyclonic circulation. The infant cyclone passed the Cape Verde Islands on the 9th, westward bound. On the 13th, at 37° W., it was reported as a cyclonic storm. By the 16th it was a full-fledged hurricane, and on Sunday, Sept. 18, 1938, it officially became the object of close attention from the hurricane-warning services of the United States Weather Bureau.

There was speculation for a time following the 1938 hurricane as to whether or not such a violent thing would literally disrupt the weather. When the records were dug out, it was found that a similar storm of 1815, for example, had been followed by a year without a summer, "eighteen-hundred-and-froze-to-death." One of the factors affecting this is believed to have been volcanic dust girdling the globe from a great eruption of Tambora in April, 1815. In general, however, there are no known long-range effects from hurricanes, however freakish or severe. There is always a possibility that slowly changing ocean temperatures, ice distribution in northern waters, or other causes contributing to an abnormal pressure distribution which directs a hurricane to New England's shore might affect the weather for a year or even several years. That would make the hurricane and subsequent weather equal products of some other general causes but would relieve the hurricane of direct responsibility for following abnormalities of weather, such as a succession of drought years after 1938.

THE NEW ENGLAND HURRICANE OF SEPTEMBER, 1944

The New England hurricane of 1815 was followed by one in 1821. The one of 1938 was followed by one in 1944. If this 6-year pairing was more than coincidence, we may have to wait a century or so for the evidence.

The general atmospheric conditions surrounding the one of 1944 were similar in many ways to those of 1938. At 4:00 P.M., EWT, on Friday, Sept. 8, 1944, San Juan, Puerto Rico, announced the presence of a tropical disturbance. On the 9th, in a novel and daring mission, two army meteorologists, Colonel Lloyd B. Woods and Major Harry Wexler, flew into the storm from the rear, went to the center under clear skies and saw an ominous bank of middle- and upper-level clouds ahead. This

established the character of the storm and fixed its location on that date at about 21° N., 60° W., a fully developed hurricane moving west-northwestward. It slowly approached the Carolinas, 1,000 miles distant, during the 10th and 11th.

During this time, a high-pressure ridge over Bermuda and the western Atlantic favored the northward movement of large volumes of tropical air over the coastal waters.

At 4:30 A.M., EWT, Wednesday, Sept. 13, 1944, the storm was near 27.8° N., 74.5° W., about 380 miles off Florida, moving northwest at 10 to 12 miles per hour. At 2:30 A.M., on Thursday, the 14th, it had just passed the point of recurvature and started northward at about 20 miles per hour. Seven hours later, it passed Hatteras, where the barometer reached 27.97 inches (947.2 millibars) and gusts of 140 to 150 miles per hour were estimated. It was advancing about 30 miles per hour at that point and rapidly undergoing the transition from a slowly moving tropical storm to a high-speed cyclone with mid-latitude habits.

The center traveled the 400 miles from Hatteras to Long Island in 11 hours. It continued to move northeastward at between 35 and 40 miles per hour, passing between Fishers Island and Block Island, across Rhode Island between Westerly and Point Judith, southeastern Massachusetts, the southeast tip of Maine, lower New Brunswick to Prince Edward Island, and then across Newfoundland. It finally merged into a low-pressure center southeast of Greenland.

The storm had the traditional eye, in which winds died down and a starlit sky emerged. This passed Providence, R. I., at 12:20 A.M., Friday, Sept. 15, 1944; South Weymouth, Mass., at 1:15 A.M.; Rockport, Mass., at 2:00 A.M.; Portland, Me., at 4:30 A.M., all EWT.

During Sept. 14, maximum winds at the surface were generally 75 to 90 miles an hour. The highest wind velocity recorded was 134 miles per hour at 12:20 P.M., Sept. 14, at Cape

Henry, Va. Maxima equaled or exceeded all previous records at Hatteras, Cape Henry, Atlantic City, New York, and Block Island.

In contrast to the time of the 1938 storm, most of New England fell within the "safe" semicircle of the 1944 storm, in addition to the fact that the latter lost some of its original energy by the time it had reached the area.

Hurricane tides did not materialize as they had in 1938 because the arrival of the 1944 storm nearly coincided with the time of scheduled low tide. Newport had an increase of 8 feet, Providence, 9 feet, and New London, 6 feet, which could be attributed to the hurricane. The maximum tide at Providence in 1938 (normal high tide plus hurricane tide) was 17.6 feet.

The American Red Cross estimated that between North Carolina and Massachusetts the 1944 storm caused the death of 46 and injury of 338, 921 houses destroyed and 16,832 damaged, 131 boats destroyed and 635 damaged. A new loss factor, unique for the 1944 storm due to intensified patrol and other war shipping activities, was the loss of 344 men and 5 vessels at sea.

The total property damage for the 1944 storm was placed at $100,000,000, as against $300,000,000 for that of 1938.

Considerable loss of life and property was avoided as a direct result of improved forecasting networks developed following the 1938 storm. These had been implemented by new tools of science.

One of the important contributions of these tools was information on the movements of air at high levels. A hurricane actually "drifts" along with the winds prevailing on its course at the time, so intimate knowledge of those winds leads to accurate prediction of the hurricane's course. In 1944, the storm was a gigantic whirling entity 500 miles in diameter at the surface, tightly closed to 10,000 feet, and spewing its entrails into the stratosphere to a height of 36,000 feet. It was literally

dragged along the earth's surface by the scruff of its neck by the upper level winds along the low-pressure trough in which it moved. It had a definite forward lean as its top tried to outrun its base.

Back in 1935, Harvard University's Blue Hill Meteorological Observatory, under the guidance of Professor Charles F. Brooks, designed and used the first radiometeorograph, a forerunner of one of the tools mentioned above. It was a package containing instruments for measuring temperature, humidity, and pressure. When borne aloft by a small balloon, it broadcast back to earth by radio the readings on its elements. A maximum height of 95,000 feet has been reached by such a device, probing the conditions continuously during the ascent and sending the answers back to earth by radio. Parallel developments at Harvard and elsewhere following this pioneer project have led to a standard form now in wide use. A logical extension of modern techniques is to arrange receiving equipment to give accurate directional fixes which would permit the addition of information on wind direction and velocity at different heights. Another method of establishing upper-air wind velocities and directions is to follow the course of a meteorological balloon by radar.

Both the radio-sounding and radar techniques were applied to the 1944 storm as it moved along the coast and contributed to making it the best observed and predicted hurricane on record. The Weather Bureau, with frequent bulletins issued along the storm's course to guide people in its path, called the story play by play with an accuracy that seemed uncanny to a layman. With the exception of one minor miss in path in the vicinity of Boston, it was a nearly perfect performance and one to give the public a sense of confidence for future cases, if any.

Standard meteorological observations of even the most modern variety, however, have not been detecting hurricanes until after they are well formed and probably several days old. In

the Pacific, the problem is even worse with typhoons. One obvious reason, of course, is that the storms frequently form over great expanses of ocean in the doldrums, where there is little or no shipping or air traffic to supply observers. An interesting development in this connection has been made in recent years by seismologists, of all people. From the earliest days of recording waves in the ground, they have been plagued periodically by "storms" of microseisms (Greek for "small shakings") which waxed and waned for hours but were in no way connected with earthquakes. Gradually it became apparent that microseisms were often connected in some way with atmospheric storms. To this day the mechanism that connects them is not understood, but from experience a great deal has been learned about the relationship. One feature, reported from St. Louis University in 1940, is that with properly spaced seismographs it is possible to determine the direction in which microseismic waves are advancing as they pass the observing point. This, combined with the fact that microseisms increase in amplitude over considerable areas whenever there is a hurricane or severe storm at sea, led to military experiments during the war aimed at testing the practicability of locating hurricanes by the use of microseisms. An experimental network was in operation during the advance of the hurricane of Sept. 9–14, 1944. Early reports on the results of the wartime investigations indicate that they were positive and highly encouraging. It seems very likely now that before long practical means will have been developed for including microseismic data in routine fashion in programs for hurricane-warning services.

CHAPTER 8

Geophysical Fables—Atlantis to Zealots

ATLANTIS

An all-time favorite among tall tales involving earthquakes, volcanoes, tidal waves, and hurricanes, is the story of Atlantis by the Greek philosopher Plato (427–347 B.C.). It is told through the words of an Egyptian priest speaking in one of Plato's dialogues, the *Timoeus.*[1] In part, it runs:

"As for those genealogies of yours which you have recounted to us, Solon, they are no better than the tales of children; for, in the first place, you remember one deluge only, whereas there were many of them; and, in the next place, you do not know that there dwelt in your land the fairest and noblest race of men which ever lived, of whom you and your whole city are but a seed or remnant. And this was unknown to you, because for many generations the survivors of that destruction died and made no sign. For there was a time, Solon, before that great deluge of all, when the city which is now Athens was first in war, and was pre-eminent for the excellence of her laws, and is said to have performed the noblest deeds, and to have had the fairest constitution of any of which tradition tells, under the face of heaven."

Solon marvelled at this, and earnestly requested the priest to inform him exactly and in order about these former citizens.

"You are welcome to hear about them, Solon," said the priest, "both for your own sake and for that of the city; and, above all, for the sake of the goddess who is the common patron and pro-

[1] Plato's *Dialogues*, ii, 517.

tector and educator of both our cities [Athene]. She founded your city a thousand years before ours, receiving from the Earth and Hephaestus the seed of your race, and then she founded ours, the constitution of which is set down in our sacred registers as 8,000 years old. As touching the citizens of 9,000 years ago, I will briefly inform you of their laws and of the noblest of their actions; the exact particulars of the whole we will hereafter go through at our leisure in the sacred registers themselves. If you compare these very laws with your own, you will find that many of ours are the counterpart of yours, as they were in the olden time. In the first place, there is the caste of priests, which is separated from all the others; next there are the artificers, who exercise their several crafts by themselves, and without admixture of any other; and also there is the class of shepherds and that of hunters, as well as that of husbandmen; and you will observe, too, that the warriors in Egypt are separated from the other classes, and are commanded by law only to engage in war; moreover, the weapons with which they are equipped are shields and spears, and this the goddess taught first among you, and then in Asiatic countries, and we among the Asiatics first adopted.

"Then, as to wisdom, do you observe what care the law took from the very first, searching out and comprehending the whole order of things down to prophecy and medicine (the latter with a view to health); and out of these divine elements drawing what was needful for human life, and adding every sort of knowledge which was connected with them. All this order and arrangement the goddess first imparted to you when establishing your city; and she chose the spot of earth in which you were born, because she saw that the happy temperament of the seasons in that land would produce the wisest of men. Wherefore the goddess, who was a lover both of war and of wisdom selected, and first of all settled that spot which was the most likely to produce men likest herself. And there you dwelt, having such laws as these and still better ones, and excelled all mankind in all virtue, as became the children and disciples of the gods. Many great and wonderful deeds are recorded of your State in our histories; but one of them exceeds all the rest in greatness and valor; for these histories tell of a mighty

power which was aggressing wantonly against the whole of Europe and Asia, and to which your city put an end. This power came forth out of the Atlantic Ocean, for in those days the Atlantic was navigable; and there was an island situated in front of the straits which you call the Columns of Hercules; the island was larger than Libya and Asia put together, and was the way to other islands, and from the islands you might pass through the whole of the opposite continent which surrounded the true ocean; for this sea which is within the Straits of Hercules is only a harbor, having a narrow entrance, but that other is a real sea and the surrounding land may be most truly called a continent. Now, in the island of Atlantis there was a great and wonderful empire, which had rule over the whole island and several others, as well as over parts of the continent; and, besides these, they subjected the parts of Libya within the Columns of Hercules as far as Egypt, and of Europe as far as Tyrrhenia. The vast power thus gathered into one, endeavored to subdue at one blow our country and yours, and the whole of the land which was within the Straits; and then, Solon, your country shone forth, in the excellence of her virtue and strength, among all mankind; for she was the first in courage and military skill, and was the leader of the Hellenes. And when the rest fell off from her, being compelled to stand alone, after having undergone the very extremity of danger, she defeated and triumphed over the invaders, and preserved from slavery those who were not yet subjected, and freely liberated all the others who dwelt within the limits of Hercules. But afterward there occurred violent earthquakes and floods, and in a single day and night of rain all your warlike men sank into the earth, and the island of Atlantis in like manner disappeared, and was sunk beneath the sea. And that is the reason why the sea in those parts is impassable and impenetrable, because there is such a quantity of shallow mud in the way; and this was caused by the subsidence of the island.". . .

Let me begin by observing, first of all, that nine thousand was the sum of years which had elapsed since the war which was said to have taken place between all those who dwelt outside the Pillars of Hercules and those who dwelt within them; this war I am now to describe. Of the combatants on the one side the city of Athens

was reported to have been the ruler, and to have directed the contest; the combatants on the other side were led by the kings of the islands of Atlantis, which, as I was saying, once had an extent greater than that of Libya and Asia; and, when afterward sunk by an earthquake, became an impassable barrier of mud to voyagers sailing from hence to the ocean. . . .

Many great deluges have taken place during the nine thousand years, for that is the number of years which have elapsed since the time of which I am speaking; and in all the ages and changes of things there has never been any settlement of the earth flowing down from the mountains, as in other places, which is worth speaking of; it has always been carried round in a circle, and disappeared in the depths below. The consequence is that, in comparison of what then was, there are remaining in small islets only the bones of the wasted body, as they may be called, all the richer and softer parts of the soil having fallen away, and the mere skeleton of the country being left. . . .

I have before remarked, in speaking of the allotments of the gods, that they distributed the whole earth into portions differing in extent, and made themselves temples and sacrifices. And Poseidon, receiving for his lot the island of Atlantis, begat children by a mortal woman and settled them in a part of the island which I will proceed to describe. On the side toward the sea, and in the center of the whole island, there was a plain which is said to have been the rarest of all plains, and very fertile. Near the plain again, and also in the center of the island, at a distance of about 50 stadia (about 5¾ miles), there was a mountain, not very high on any side. . . .

There follow details of the island's government according to the laws of Poseidon. For many generations all went extremely well. There was no fighting and avarice was unknown.

. . . by the continuance in them of a divine nature, all that which we have described waxed and increased in them; but when this divine portion began to fade away in them, and became diluted too often, and with too much of the mortal admixture, and the

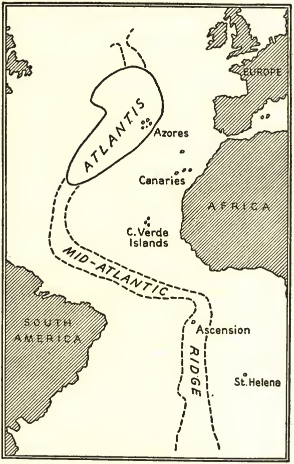
human nature got the upper hand, then, they being unable to bear their fortune, became unseemly, and to him who had an eye to see, they began to appear base, and had lost the fairest of their precious gifts; but to those who had no eye to see the true happiness, they still appeared glorious and blessed at the very time when they were filled with unrighteous avarice and power.

The story ends abruptly just as Zeus called together a meeting of all the gods in the center of the world to consider the problem. We know, however, from the introduction that the Atlantides became aggressors, conquered the inhabited world except Greece and Egypt, were defeated by the Greeks, and ultimately, with the Greek expeditionary force, wiped out by a catastrophic contretemps produced by earthquakes, volcanoes, tidal waves, and hurricane rains.

Plato's story is pure political philosophy. It points up the prosperity that results when pious, law-abiding, industrious pioneers develop a civilization that prospers in peace and the fate which awaits that civilization when it falls apart in the midst of avarice, aggression, bickering and sloth. Plato would have been chagrined and disheartened indeed had he known that over 2,000 years after he spun his yarn with a moral, citizens of an age fantastic beyond belief would be tearing at each other's throats exactly according to the pattern of his prophecies, in tiresome repetition of the actions of previous civilizations on whose bones they trod, while they remembered his story only for the legendary destruction of Atlantis by earthquakes and its disappearance beneath the sea.

The island of Atlantis, by Plato's account, "was larger than Libya and Asia put together, and was the way to other islands. . . ." This, taken even in the light of the "Libya and Asia" known to Plato (see maps of Hecateus and Herodotus), is larger than any of the present-day islands of Great Britain, the Azores, Madeiras, or Canaries. There is no evidence at present known to support the belief that any such land mass

foundered in the Atlantic within the past 11,000 years. Attempts to relate this supposed event in some way to the topo-



One attempt to guess a location for Plato's mythical Atlantis.

graphic feature traversing the bottom of the Atlantic Ocean as the Mid-Atlantic Ridge are too farfetched to warrant serious discussion. The ridge lies under roughly 10,000 feet of water as

compared with the average of nearer 15,000 feet for the ocean elsewhere. There seems to be no doubt that Plato's account is strictly imaginative in its geological features. His explanation that oceanic islands are erosional remnants of continents is, of course, erroneous as well. We might as well send out an archaeological expedition to search for Lewis Carroll's *Wonderland* or Bacon's *New Atlantis* as a submarine to find Plato's *Atlantis*.

It has been argued that the human mind is incapable of pure invention, so there must have been something to give Plato a start. The Azores and other Atlantic islands are more than sufficient for that. Atlantis can easily be understood as a compound of hearsay accounts of actual inhabited islands outside the Straits of Hercules, with Mediterranean experiences with earthquakes and volcanic islands.

MAN-MADE VOLCANIC ERUPTIONS AND EARTHQUAKES

Soon after the outbreak of World War II, suggestions began to get around that explosives be used in some form to stimulate the forces of nature as weapons of war. Early among these was the one that volcanoes be bombed behind enemy lines to start eruptions. It was assumed without argument that an "eruption" would be a deadly blow to the enemy.

The first versions reached the United States by press dispatches from England in 1940 as proposals that bombs be used to start an eruption of Vesuvius. After Pearl Harbor, the idea was revived with Fuji as the objective. In the Pacific Theater there were persistent stories that United States Army Air Forces planes had dumped several loads of heavy bombs down the throat of a volcano in New Guinea.

On Jan. 13, 1942, the proposal was given a new slant and reduced to a blueprint. This version suggested sinking two

bombs, each of 5 to 10,000 tons of TNT, offshore from Japan at depths of about 2 and 6 miles and lined up on Fuji. It was suggested then that detonation of the deeper one, followed at a proper interval by the shallower, would send a cumulative concussion into the ground that would rupture the bottom, force large quantities of water into the "probable volcanic area" and produce a man-made cataclysm. This blueprint for catastrophe showed Fuji as the target and overlooked the active volcano Mihara on the island of Oshima almost directly in line between the bombs and Fuji. Its author, however, was a truly sincere citizen who sent the scheme only to certain authorities and experts with a view to preserving secrecy if the plan were feasible.

In a somewhat different category, however, was a college professor of geology who embarrassed members of his profession by publishing on Jan. 25, 1942, and Jan. 14, 1945, newspaper articles on how to produce man-made earthquakes as well as volcanic eruptions in Japan. That tore it. One could say "poppycock" or some scientific equivalent to the Vesuvius stories in the easy days of 1940; "naughty, naughty," to the Air Forces boys who wasted bombs in New Guinea; or "sorry, sir, but your premises are definitely incorrect," to the earnest gentleman from Des Moines; but when a professor of geology in a reputable university drew pictures and signed a story showing how a handful of well-placed bombs would cause Japan literally to blow itself off the map through the release of pent-up internal forces, no simple phrase would brush it off. It required full rebuttal with chapter and verse.

The geologist's story was timed by announcements from seismographic stations that on Thursday, Dec. 7, 1944, their records revealed that there had been a tremendous earthquake near Japan. He said:

> While the prime objective of our Saipan-based bombers has been the great war industries of the Nipponese empire, there is a real possibility that the hammering of our giant missiles helped

touch off the great earthquake that struck Japan on . . . the third anniversary of Pearl Harbor.

Almost exactly three years ago, on January 25, 1942, I prepared an article . . . which first suggested the great potential value for the United States of bombing Japanese volcanoes. I said then: "You may be sure that the Japanese are well aware of the dangers of a bombing attack. Only there is nothing they can do about it. Once the furies of the earth's internal fires are released, the terrible perils of Dante's inferno pale into insignificance. If ever volcanoes are to be given an emetic, now is the time to do it when armed strife stalks the earth. Some one-ton bombs marked 'Made in U.S.A.' might be just what the doctor ordered."

Because of the war we do not know exactly what damage was done in the recent earthquake, but we do know, from seismograph records the world over, that the shock was extremely severe and lasted for six hours.

. . . While trying to minimize talk of damage, the Japs themselves tell of ruined homes and factories and of great tidal waves that swept harbors . . .

Japan is indeed vulnerable to bombing because the islands are a kind of geological house of cards resting on vast pent-up forces deep within the earth that are just waiting for a chance to escape.

Tiny disturbances in the earth's crust, when they occur in Japan, can sometimes produce earthquakes far out of all proportion to the original, initial shock.

Back in 1942 I said that a well-placed bomb could weaken the plugs of Japanese volcanoes so these rocky lava obstructions might crack and release subterranean fury, just as taking a cork from a bottle of champagne causes an explosion.

Everyone knows it isn't necessary to pull the cork from the bottle completely, for the internal pressure blows it out with a familiar "pop" at the last instant. The same thing is true with a volcano.

Is it merely coincidental that following General Doolittle's first air raid on Japan the volcano of Aso San erupted and that—on the other side of the world in Italy—Mt. Vesuvius erupted just after the violent battles at Naples between American and German troops? I think not.

Perhaps, too, that great hole in the Pacific called the Tuscarora

Deep—near Japan—enters the Nipponese earthquake picture. This great pit, that goes more than 20,000 feet beneath the Pacific waters, probably serves as another escape vent for much of the molten lava and gases which lie under Japan.

It might be possible for American submarines to "lay" depth charges in Tuscarora Deep that would sink to the bottom and be automatically exploded. If such deep sea bombing could temporarily block the volcanic escape vents, then the underground pressure would be built up until something had to break. That something, one might hope, would be the crustal surface of Japan, resulting in an earthquake.

The earthquakes result, of course, because the rocks—formerly buoyed up by internal pressures—begin to sink of their own weight. This slippage, at earthquake fault lines, creates the disastrous shocks.

You may be sure that the Japanese know of these hazards and are thinking about them every time new bombs drop from the B-29s over Tokio.

In fact the Japs knew it in 1924 when an American fleet entered the Bay of Tokyo, and the Japanese asked that no large guns be fired in an exchange of salutes.

There are two general principles to bear in mind in examining all these proposals and speculations. One is that you cannot fire an unloaded gun by pulling the trigger. Another is that you cannot fire even a loaded gun, much less an unloaded one, by tickling it with a feather.

The "geologist's" proposals can be examined best because they were reduced to writing and illustrated. His ignorance of even the rudiments of knowledge about earthquakes is shown by his words, "but we do know, from seismograph records the world over, that the shock was extremely severe *and lasted for six hours.*" The fact was, of course, that the quake lasted for a matter of seconds at its source. It was large enough to cause waves that coursed around and through the globe by various paths at different speeds in such a way that distant stations re-

corded some kind of motion for nearly six hours before they had all checked in.

The location of the earthquake of Thursday, Dec. 7, 1944, was latitude 33° N., longitude 137° E., over 100 miles from the nearest bombs that had been dropped up to that time. On the other hand, Japan has many small earthquakes every day within its borders and even the smallest exceeds by a tremendous amount a TNT bomb or an atomic bomb in energy of impact on the ground. If "tiny disturbances in the earth's crust, when they occur in Japan, can sometimes produce earthquakes far out of all proportion to the original, initial shock," then some of these daily minor earthquakes should trigger major catastrophes, which in turn should trigger neighboring regions in a chain reaction that would make pikers of atomic physicists.

We are offered what is apparently intended as observational proof in the form of, "Is it merely coincidental that following General Doolittle's first air raid on Japan the volcano of Aso San erupted . . . ? I think not."

Aso volcano is on northern Kyushu, 535 miles from Tokyo. The earthborne vibrations from that scattered handful of bombs on Tokyo could not be felt even a mile away. If these vibrations in Tokyo pulled a trigger under Aso, why was there no eruption following the earthquake of Dec. 7, 1944, which was less than half as far from Aso, though earth waves from it literally shook the entire globe? Or, if there is special magic in U.S.-made explosives, where was Aso when the atoms burst, with a force never before so concentrated by man, over Hiroshima 125 miles away on one side of it and over Nagasaki 60 miles away on the other?

"Back in 1942 I said a well-placed bomb could weaken the plugs of Japanese volcanoes so these rocky lava obstructions might crack and release subterranean fury, just as taking a cork from a bottle of champagne causes an explosion."

The illustration that accompanied that remark indicated that the volcano Mihara on the island of Oshima in Sagami Bay was the target under discussion. Mihara has not had a plug in its throat as far back as the records go. On Saturday, Mar. 29, 1924, I personally looked down that throat about as

Artist's eye view of a proposal for triggering catastrophic forces by bombing a volcano.

far as the tonsils and heard the roar and swish of rhythmically escaping gases that had free access to the open air downwind from my perch. Japanese scientists reporting minor activity from time to time over succeeding years confirmed continuance of that condition. Of course, some volcanoes have sealed themselves off at the top, but if the pressure from within trying to blow the cork out is less than that produced by explosion of a one-ton bomb (as it would have to be if the bomb is supposed

to do the job the internal pressures can't), then we can predict that the results following successful removal of a cork will have all the violent significance of a sneeze in the middle of a desert on a quiet June night.

Finally we come to the proposed submarine operations in the Tuscarora Deep. It might seem like ducking the issue to point out that the seaward slopes of Oshima Island do not dip down into the Tuscarora or any other ocean deep or come within 200 miles of doing it. On the other hand, if we want to hope that violent disruption of the ocean bottom by bombs will (a) seal off vents and cause accumulation of intolerable pressures or (b) open fissures and allow sea water to contact "intensely heated and more or less molten interiors" and cause explosions, we have the evidence of a gigantic laboratory test that it doesn't work. On Saturday, Sept. 1, 1923, one of the world's largest earthquakes occurred under Sagami Bay between the volcanoes of Mihara on Oshima and Fuji on the mainland, dead center in the shell of the "intensely heated interior." It caused under Sagami Bay the greatest changes in sea-bottom topography ever charted and applied to the entire Pacific coast of central Japan a blow of greater energy than could be produced by the sum total of all explosives made by man since history began. Nothing happened to either Fuji or Mihara.

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